Deep (photometric & spectroscopic) Surveys of the Fornax cluster

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VST color composite image

Why Fornax?

RA	03h 38m
DEC	-35d 30m
distance	20 Mpc (Ferrarese et al. 2000)
M_{dyn}	$7 \times 10^{13}\ M_{\odot}$ (Drinkwater et al. 2001)
L_X	5×10^{41} erg/s (Jones et al. 1997)
σ	370 km/s (Drinkwater et al. 2001)
R_{vir}	0.7 Mpc (Drinkwater et al. 2001)

- nearby, dense environment
- the mass assembly is still ongoing

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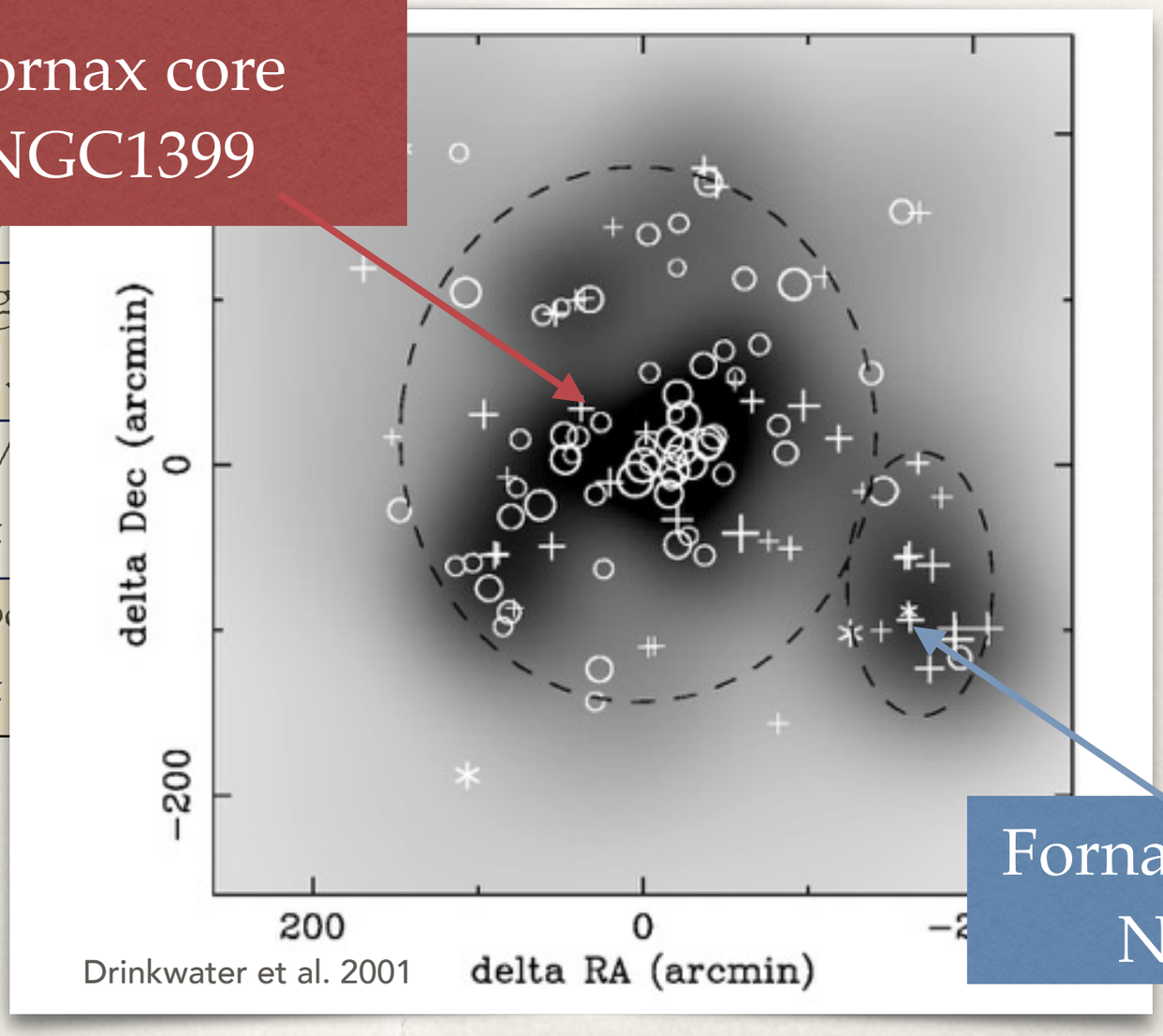

FDS: the SW group

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Why Fornax?

multi-wavelength observations available/upcoming

- **Herschel survey** R≤16 deg^2 (P.I. Davies): cold dust in ~30 ETGs & LTGs
- **ALMA survey** on the Herschel sample (P.I. Davis)
- **SAMI integral field spectroscopy** of ~100 dwarf galaxies (P.I. Scott)
- **MUSE survey** of the Fornax members inside R_{vir} (P.I. Sarzi/Iodice)
- **Fornax Deep Survey (FDS)** with VST (P.I. Iodice/Peletier)
- **MUSE survey of dwarfs** (P.I. Peletier)
- **VIMOS Survey of GCs** (P.I. Napolitano)
- **MeerKAT HI survey of Fornax** (P.I. Serra)
- **VISTA data** (P.I. Puzia)
- **Archival data: Chandra, HST, GALEX**

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This talk:

1. Fornax Deep Survey with VST

2. results on stellar halos & LSB

3. next from Fornax3D with MUSE

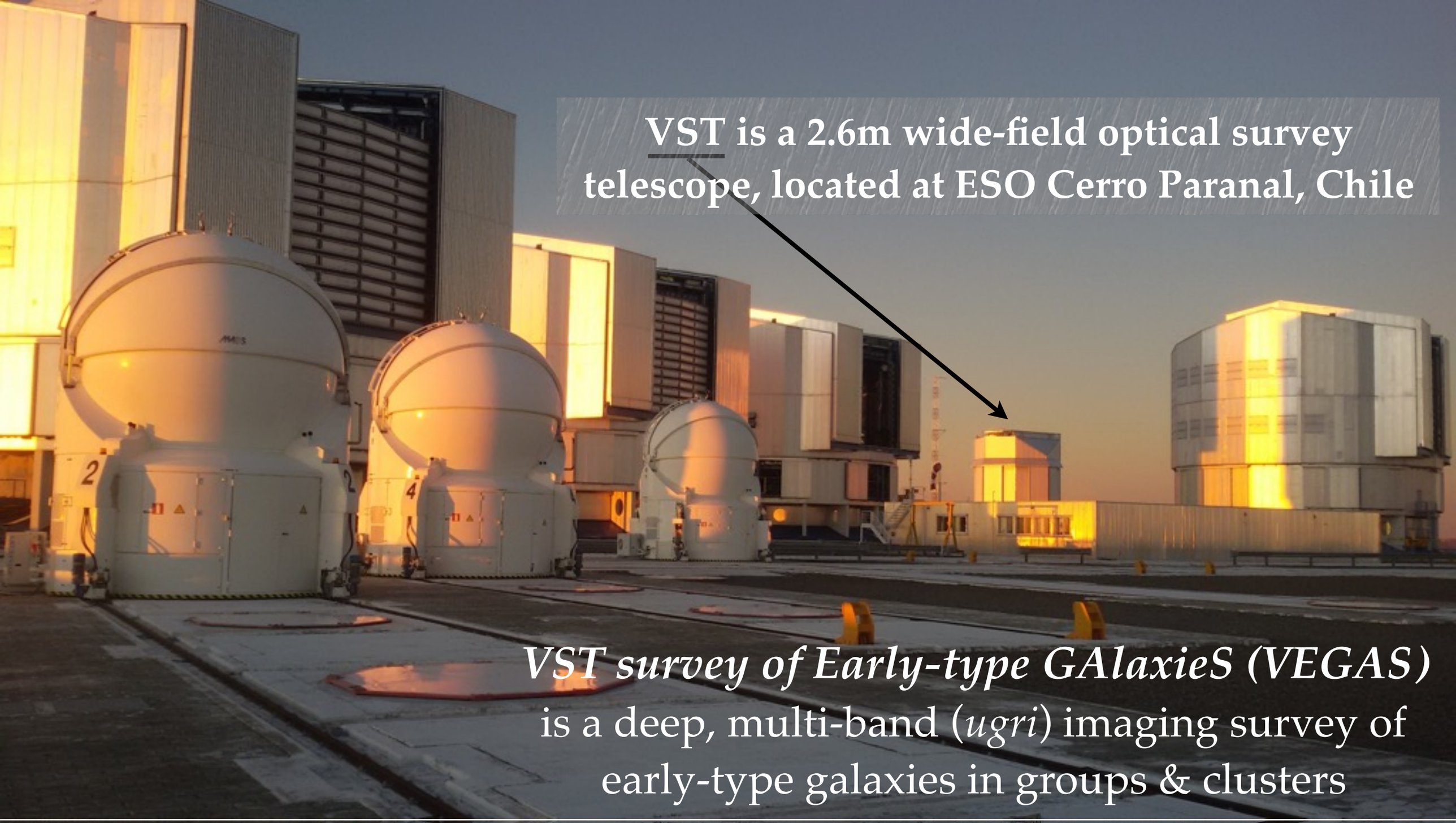
The Fornax Deep Survey with VST

- joint project based on

  INAF GTO for VEGAS (P.I. E. Iodice)
  &
  OmegaCam GTO (FOCUS, P.I. R. Peletier)

- new, multi-imaging (u, g, r, i bands) survey of the Fornax Cluster

- FDS aims to cover 26 deg^2 around the core of the Fornax cluster out to the virial radius, including the region of Fornax A



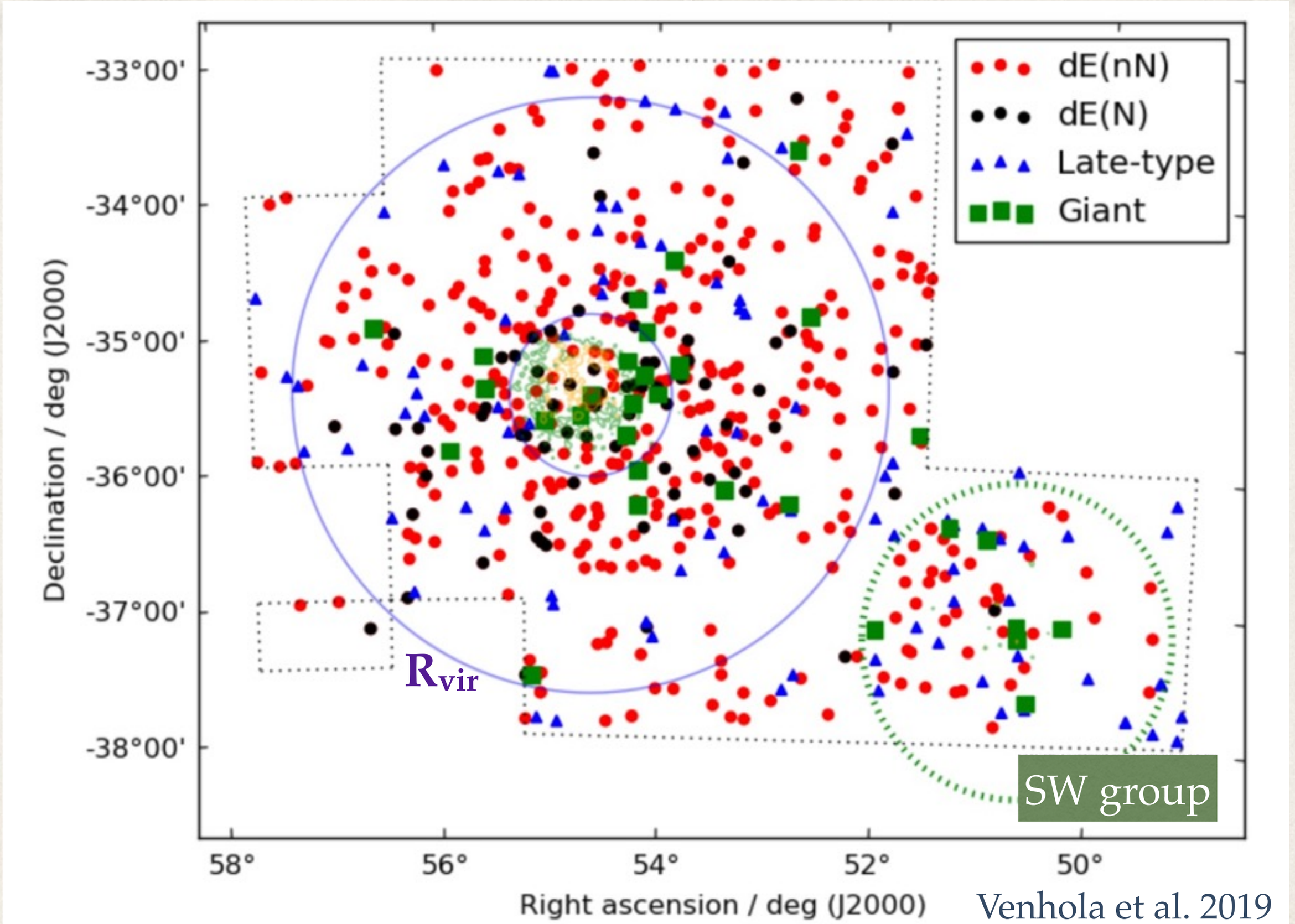
VST is a 2.6m wide-field optical survey telescope, located at ESO Cerro Paranal, Chile

VST survey of Early-type GAlaxieS (VEGAS)
is a deep, multi-band (*ugri*) imaging survey of
early-type galaxies in groups & clusters

VEGAS is based on the GTO assigned at INAF

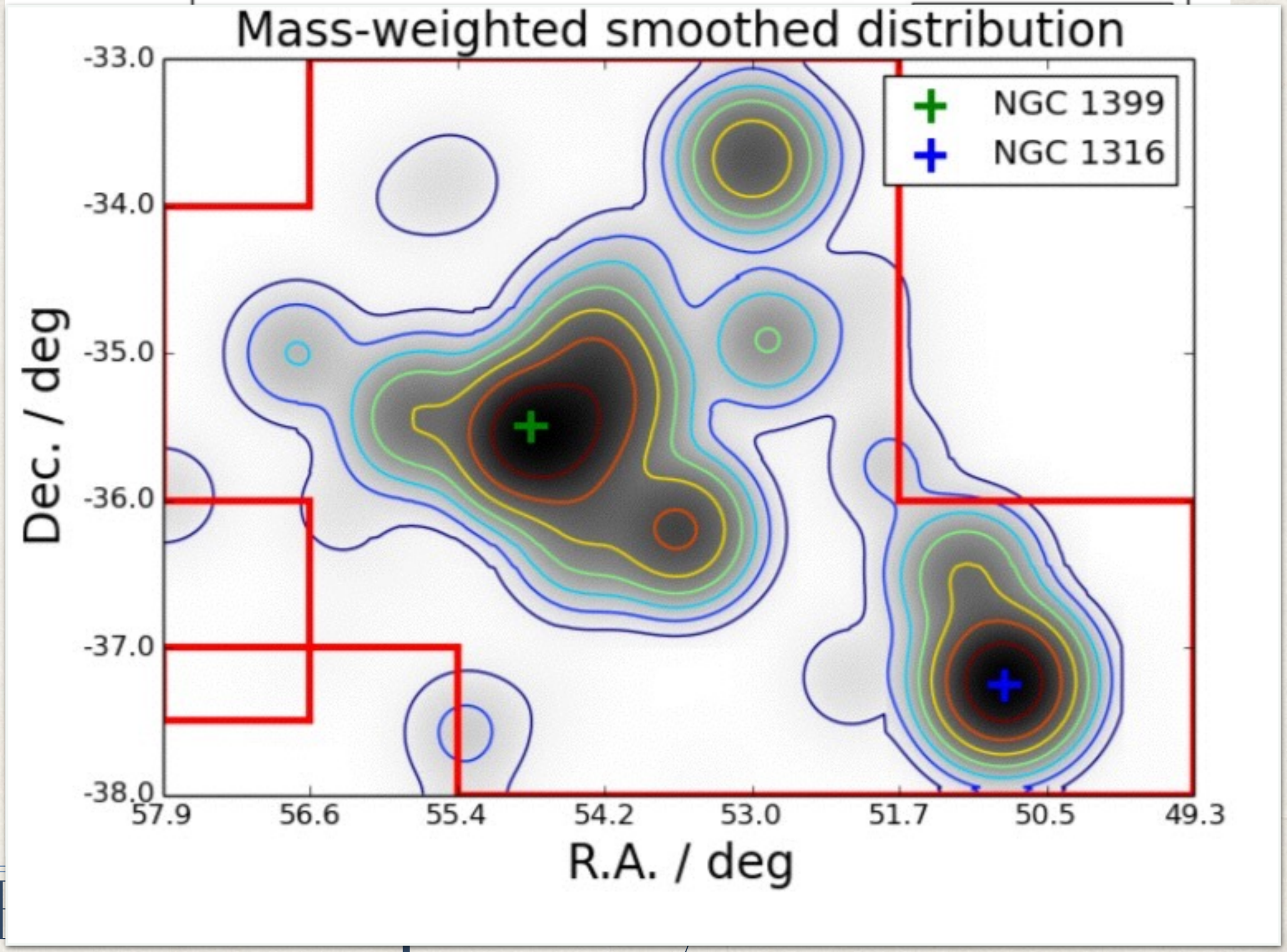
- 2011-2016, PI: M. Capaccioli, ~55 nights
- 2016-2021, PI: E. Iodice, ~62 nights

http://www.na.astro.it/vegas/VEGAS/Welcome.html



Venhola et al. 2019

Fornax Deep Survey with VST: area

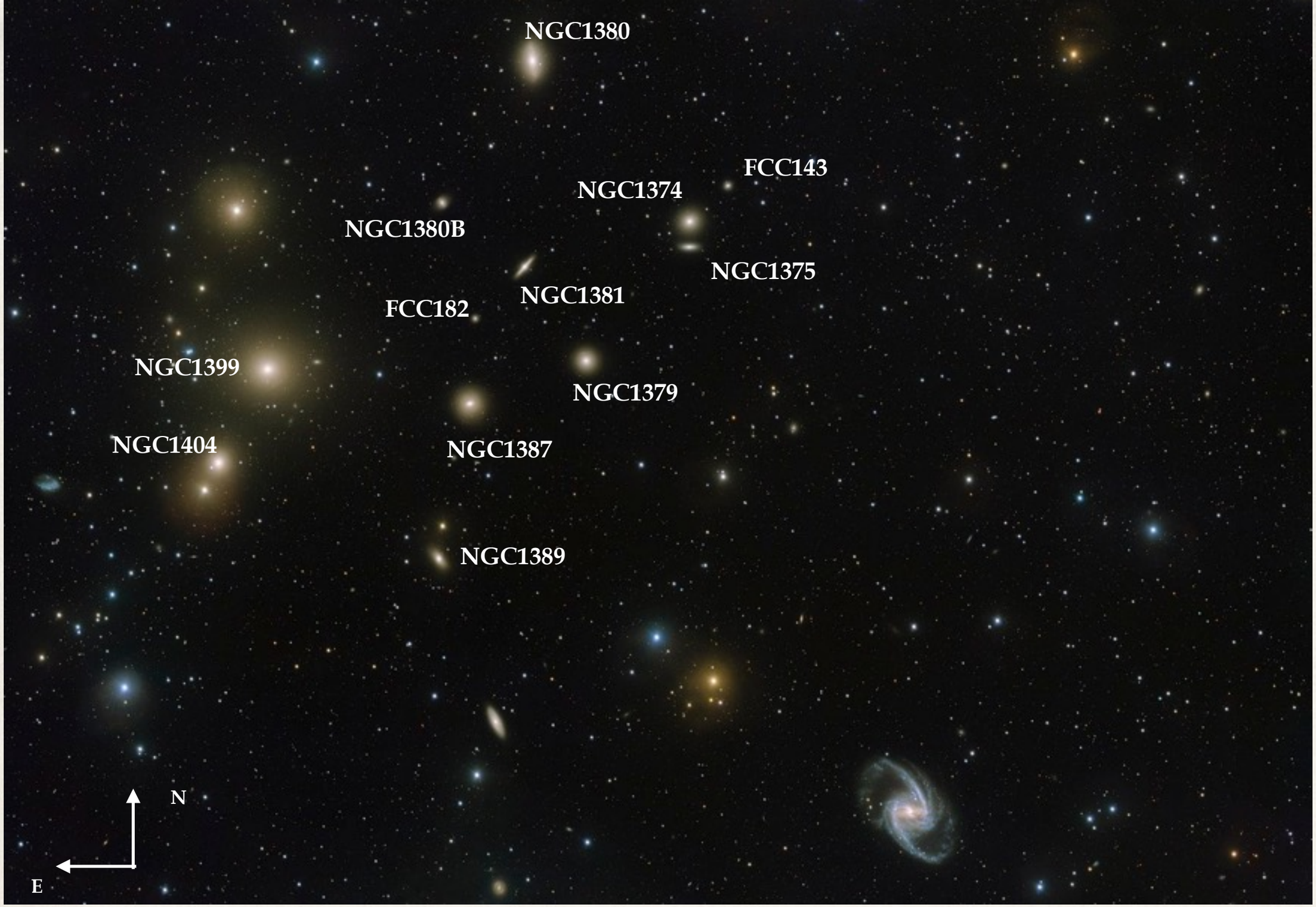

Mass-weighted smoothed distribution
NGC 1399
NGC 1316
-33.0
-34.0
-35.0
-36.0
-37.0
-38.0
Dec. / deg
57.9
56.6
55.4
54.2
53.0
51.7
50.5
49.3
R.A. / deg

- structure of the bright galaxies (m_B<15mag) inside R<R_{vir}
  (Iodice et al. 2019; Raj et al. 2019)
- stellar halos in ETGs
  (Iodice et al. 2016, 2017a, 2017b)
- LSB & Dwarf galaxies
  (Venhola et al. 2017; 2018; 2019)
- science on background objects
- GCs distribution
  (D' Abrusco et al. 2016; Cantiello et al. 2018)

Fornax Deep Survey with VST: science

P.I.: R. Peletier & E. Iodice

FDS team: M. Cantiello (INAF); J. Falcon-Barroso (IAC); A. Grado (INAF); M. Hilker (ESO); S. Mieske (ESO); N.R. Napolitano (INAF); M. Paolillo (UniNa); P. Schipani (INAF); M. Spavone (INAF); C. Spiniello (INAF); G. van de Ven (ESO); A. Venhola (Kaypten)



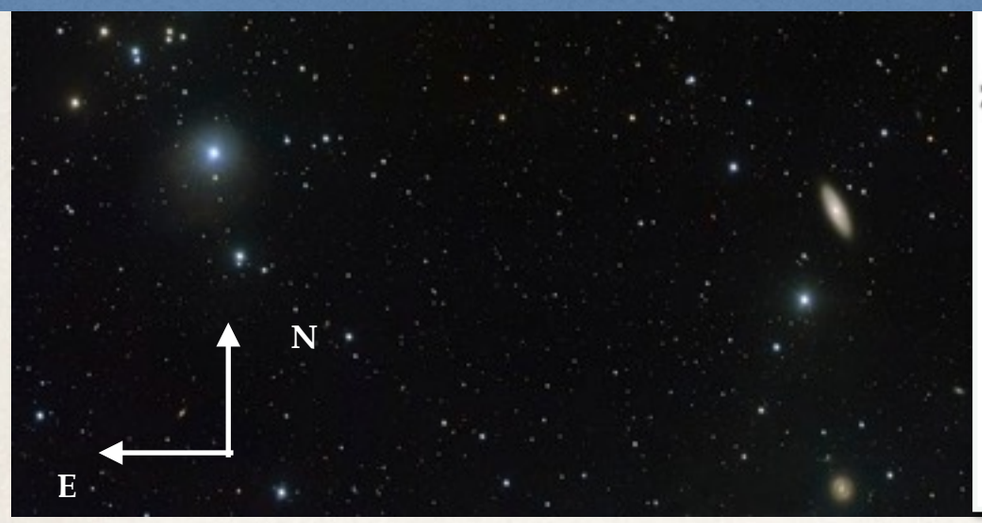
What is the new contribution from the FDS?

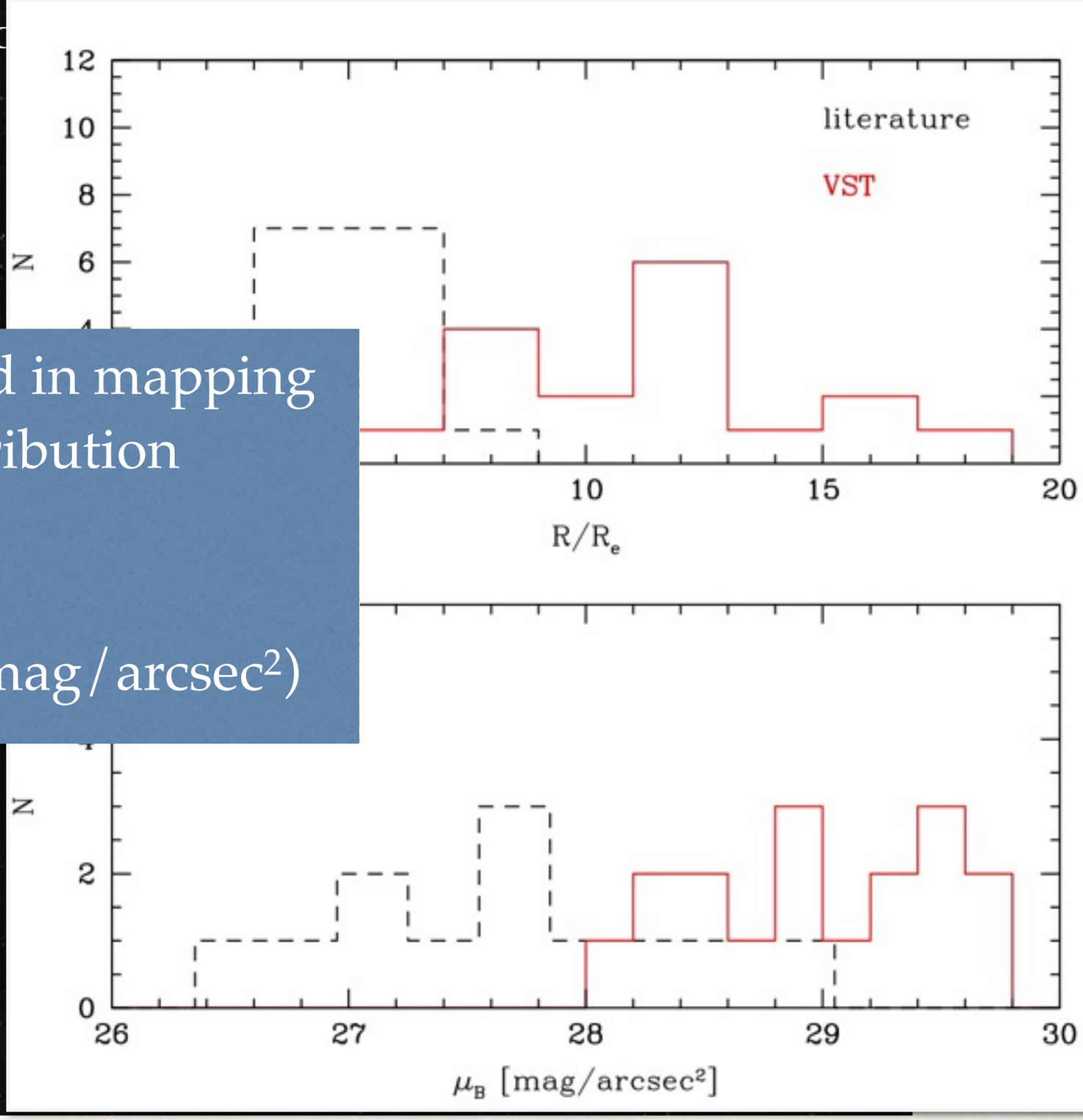
Iodice et al. 2019, A&A, 623, A1

unprecedented limits reached in mapping the light and color distribution

$\sim 10 - 15 R_e$

$\mu_r \geq 27$ mag/arcsec^2 ($\mu_B \geq 28$ mag/arcsec^2)





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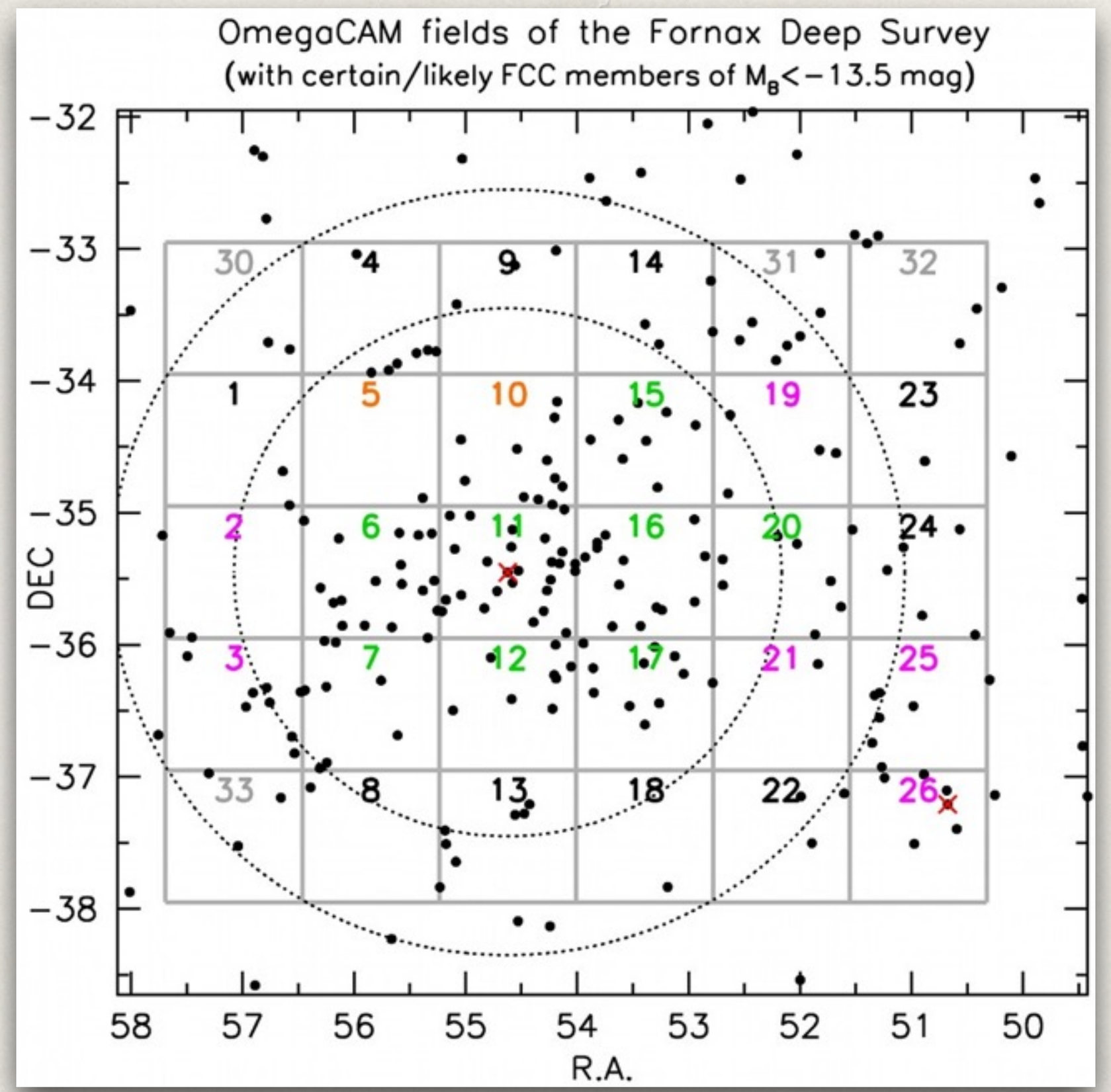
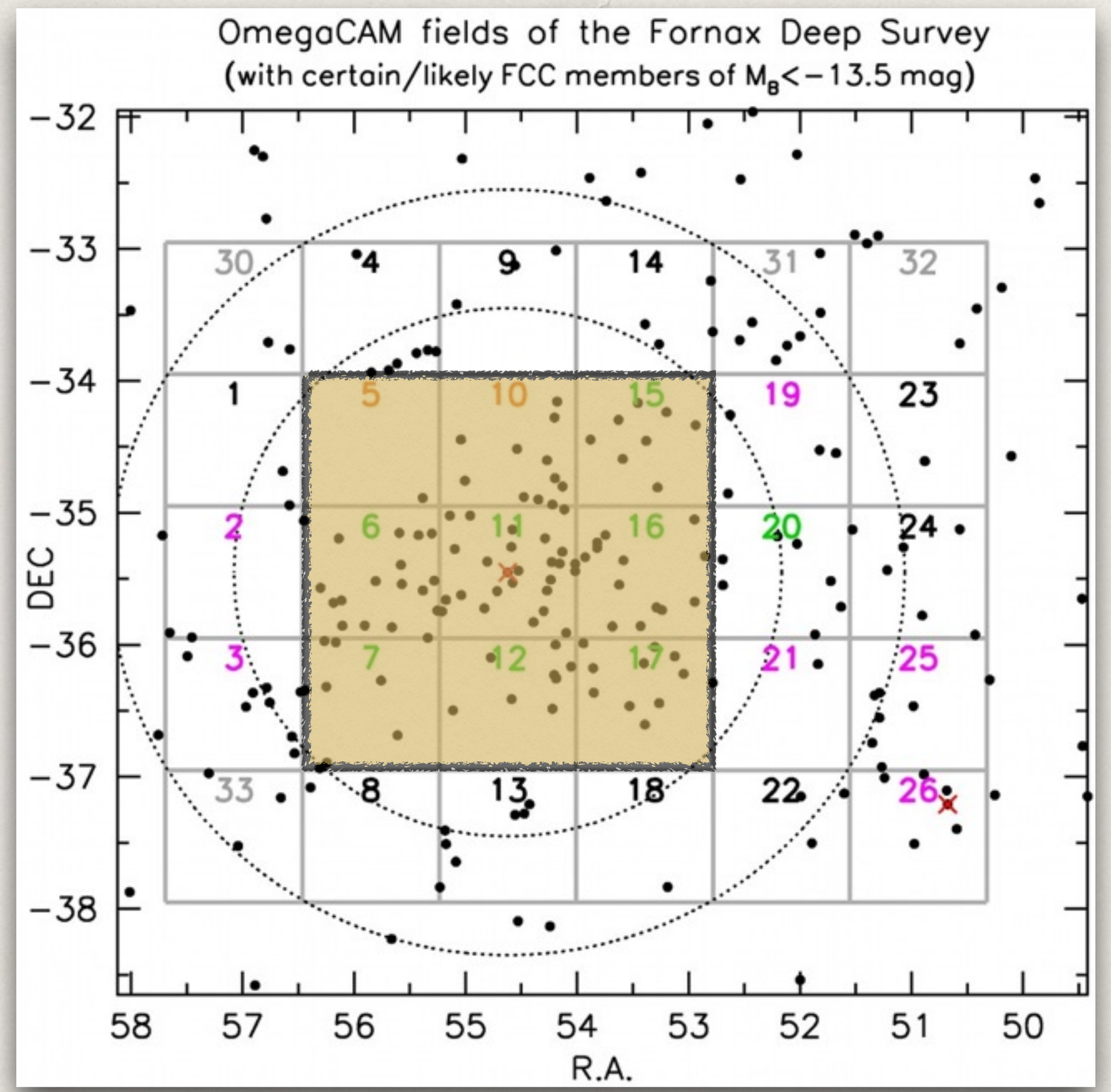
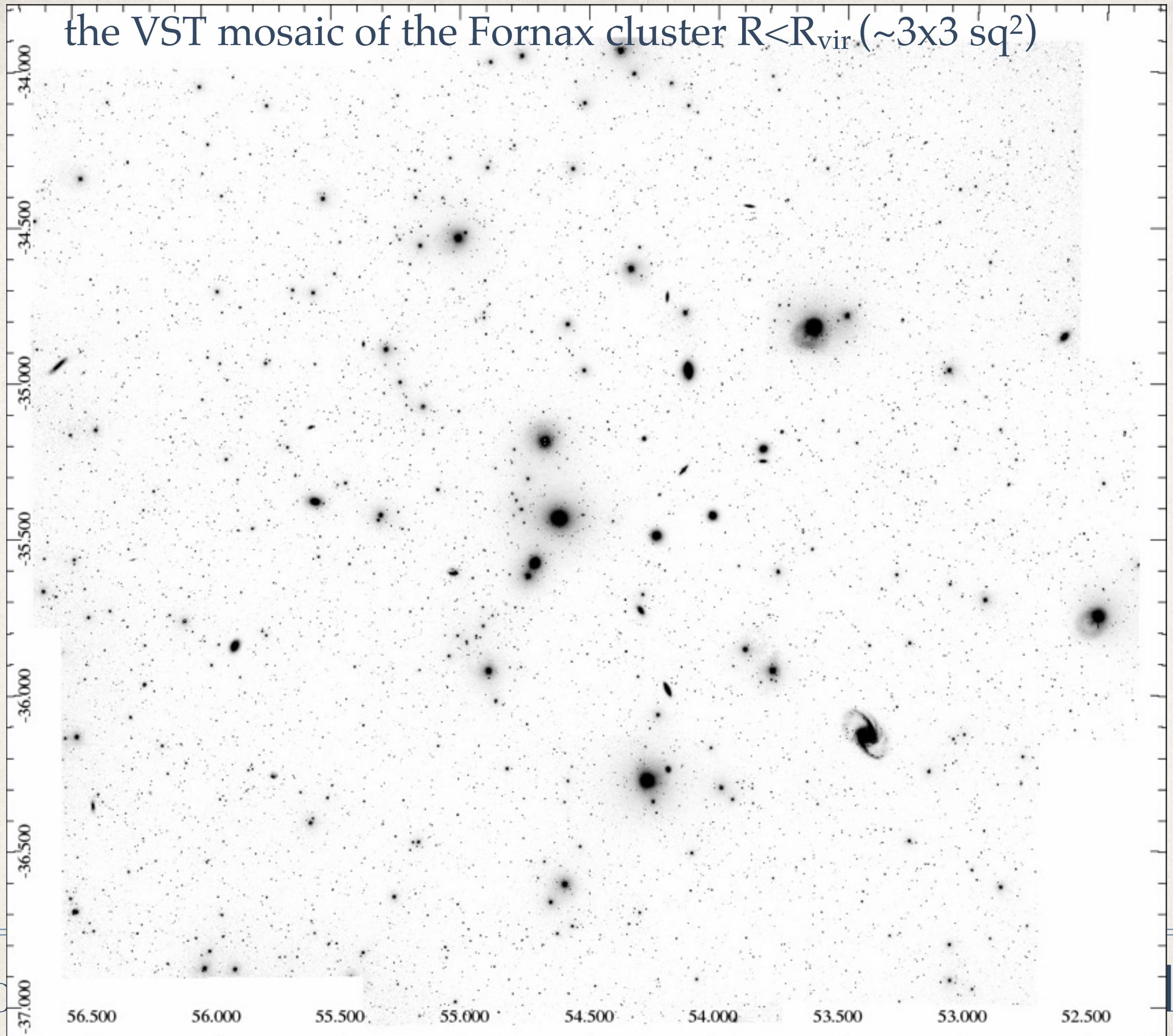


Fornax Deep Survey with VST: the virial radius



Fornax Deep Survey with VST: the virial radius

the VST mosaic of the Fornax cluster $R<R_{vir}$ (~3x3 sq^2)



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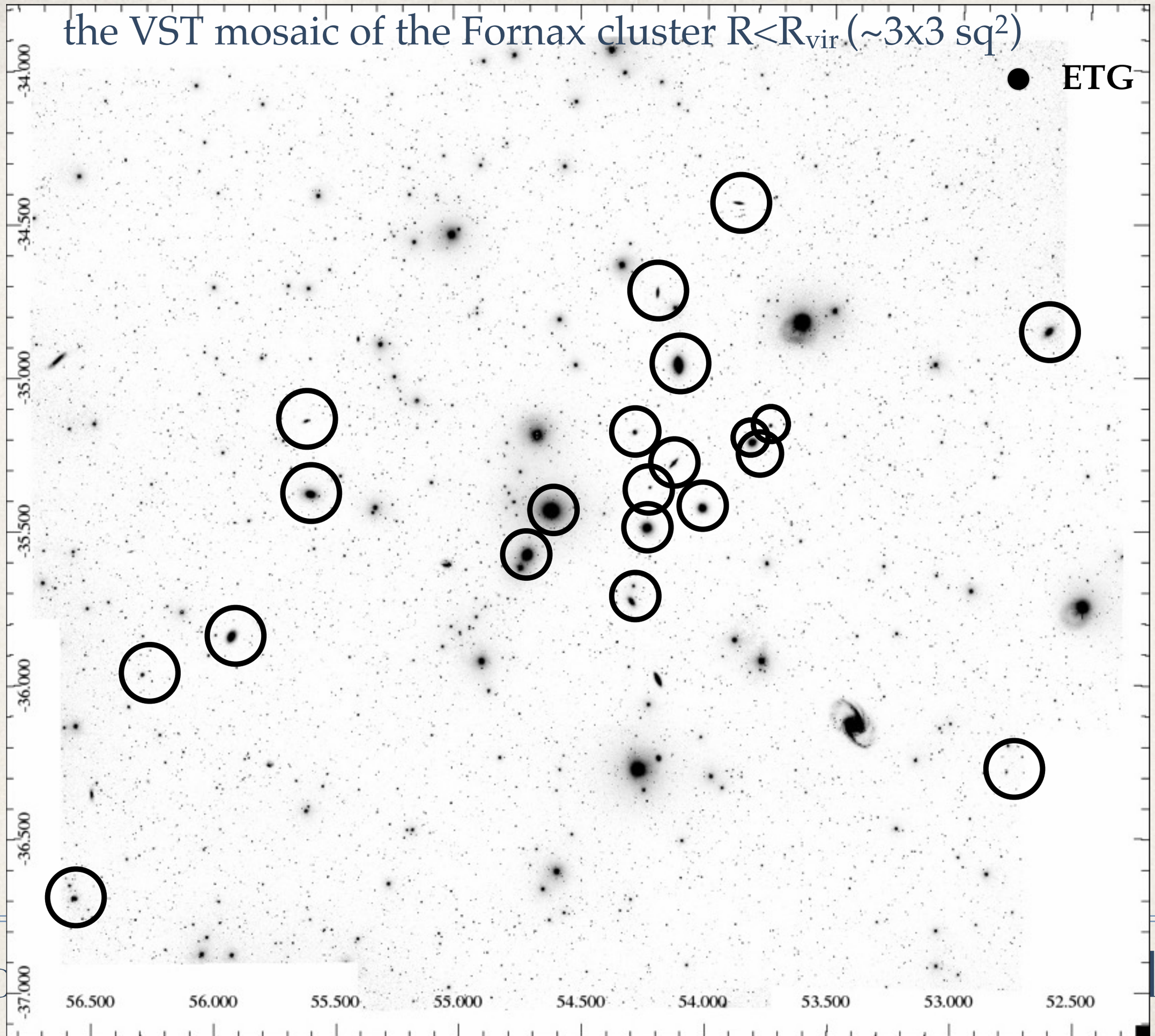

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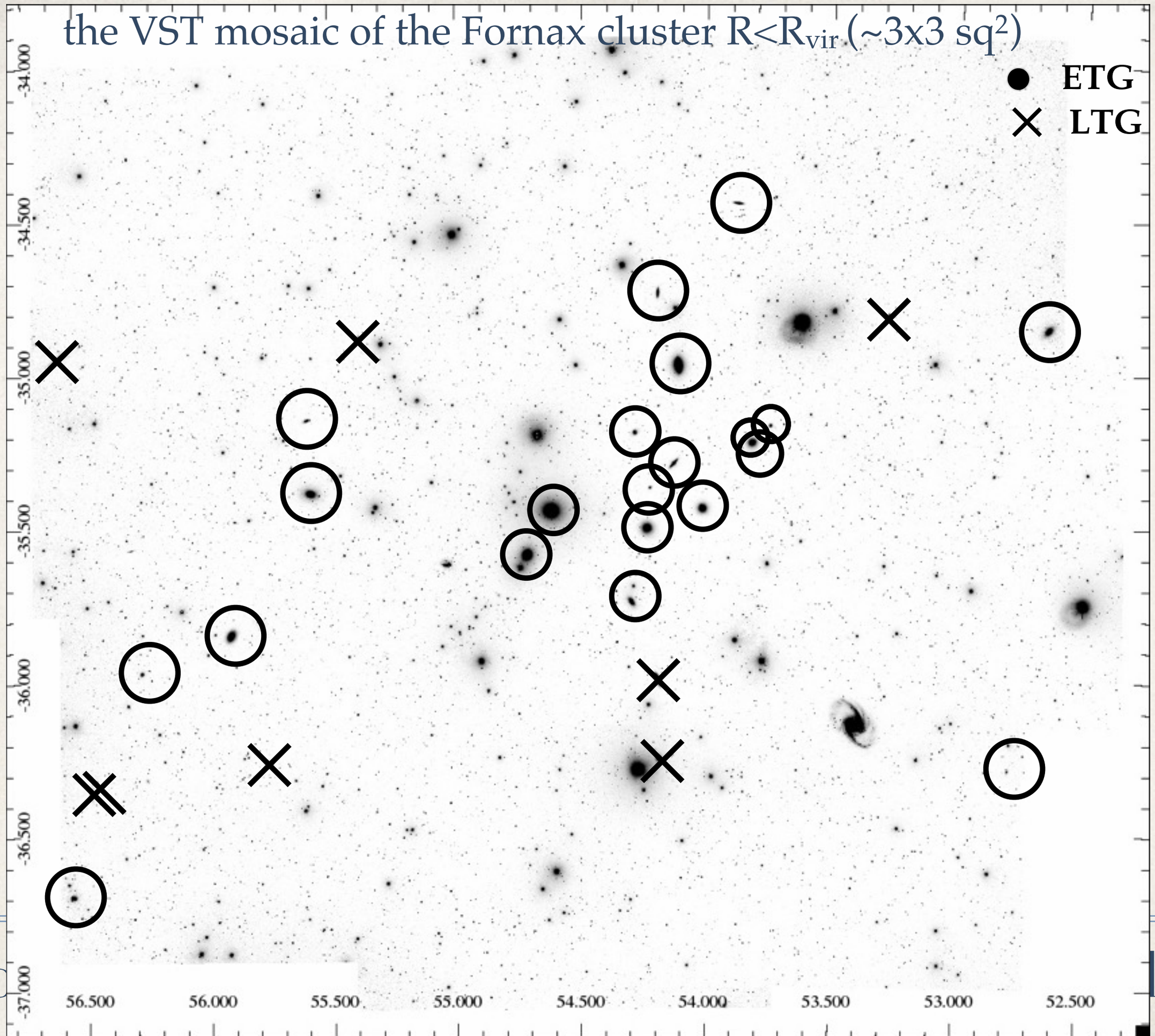

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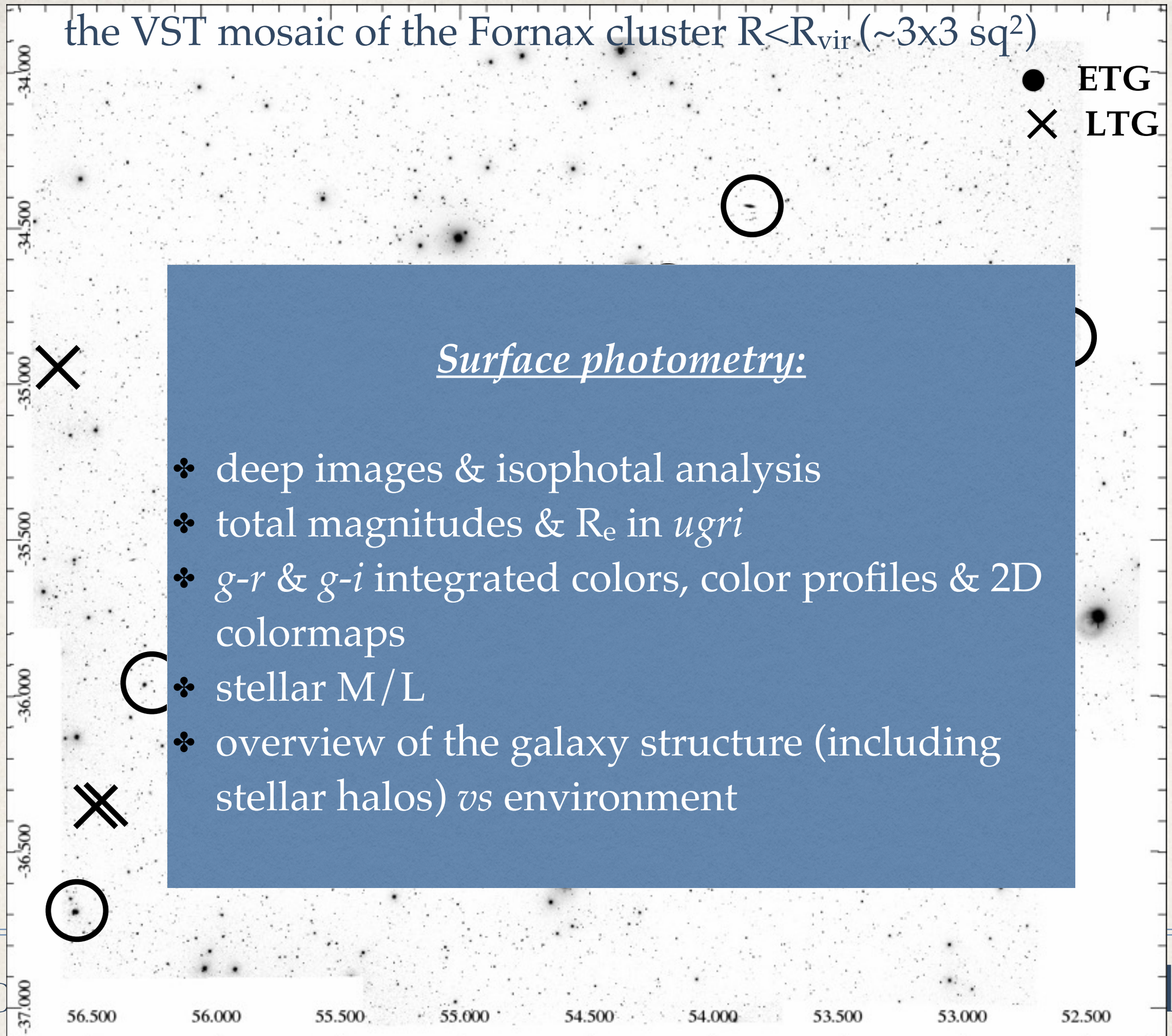
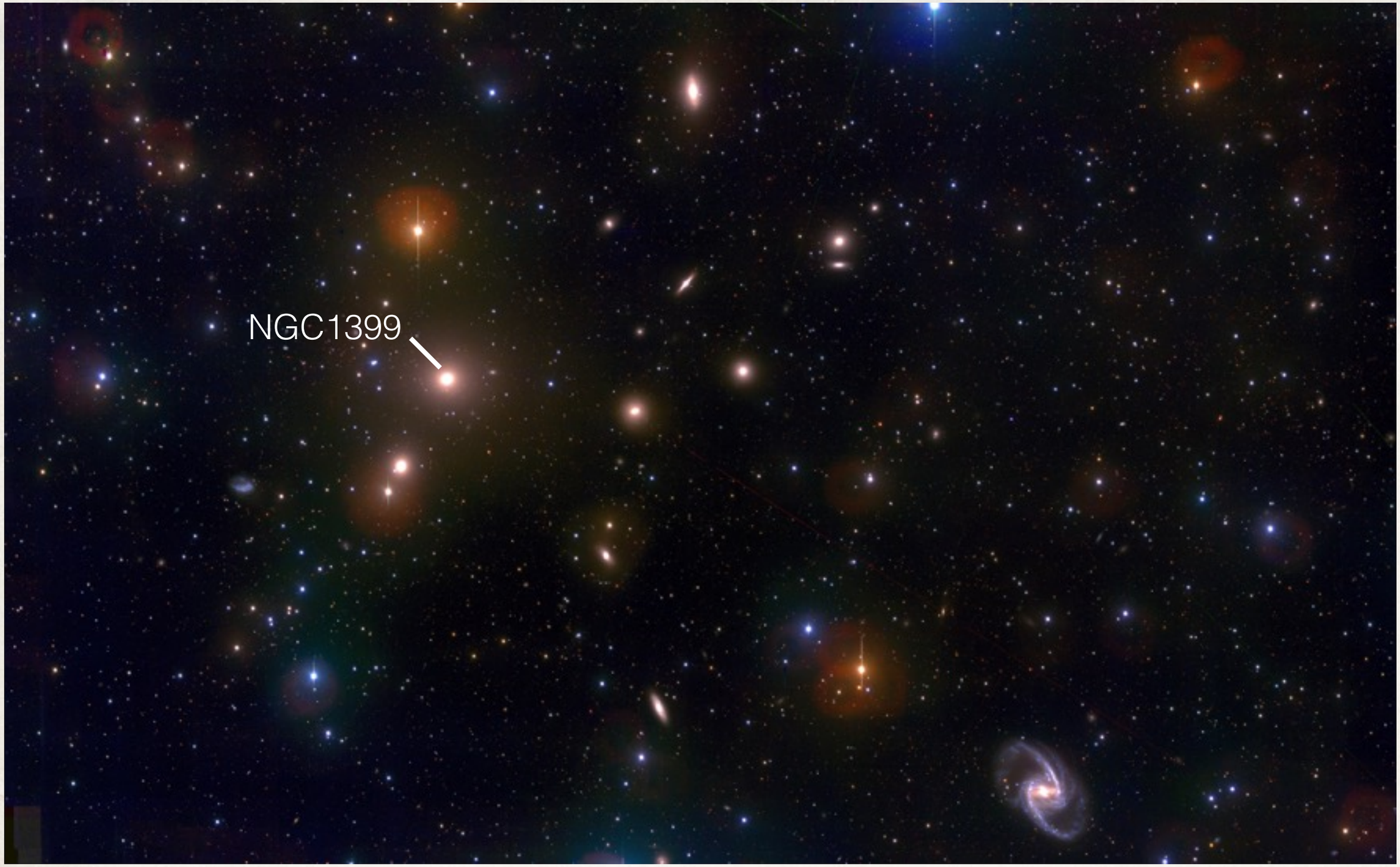


Surface photometry:

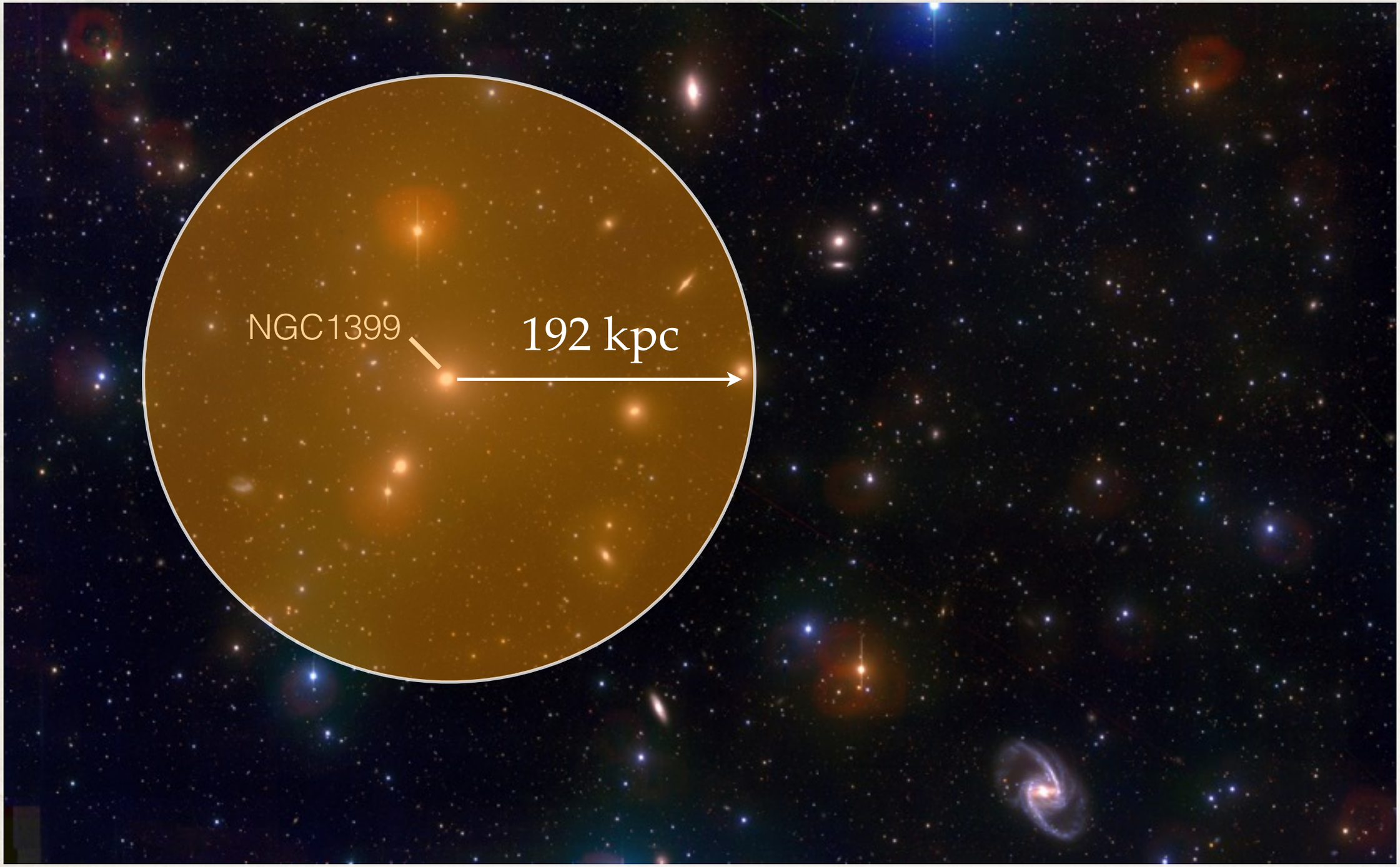
- deep images & isophotal analysis
- total magnitudes & R_e in *ugri*
- *g-r* & *g-i* integrated colors, color profiles & 2D colormaps
- stellar M/L
- overview of the galaxy structure (including stellar halos) *vs* environment

Fo lius



The extended stellar halo of NGC1399

Iodice et al. 2016, ApJ, 820, 42



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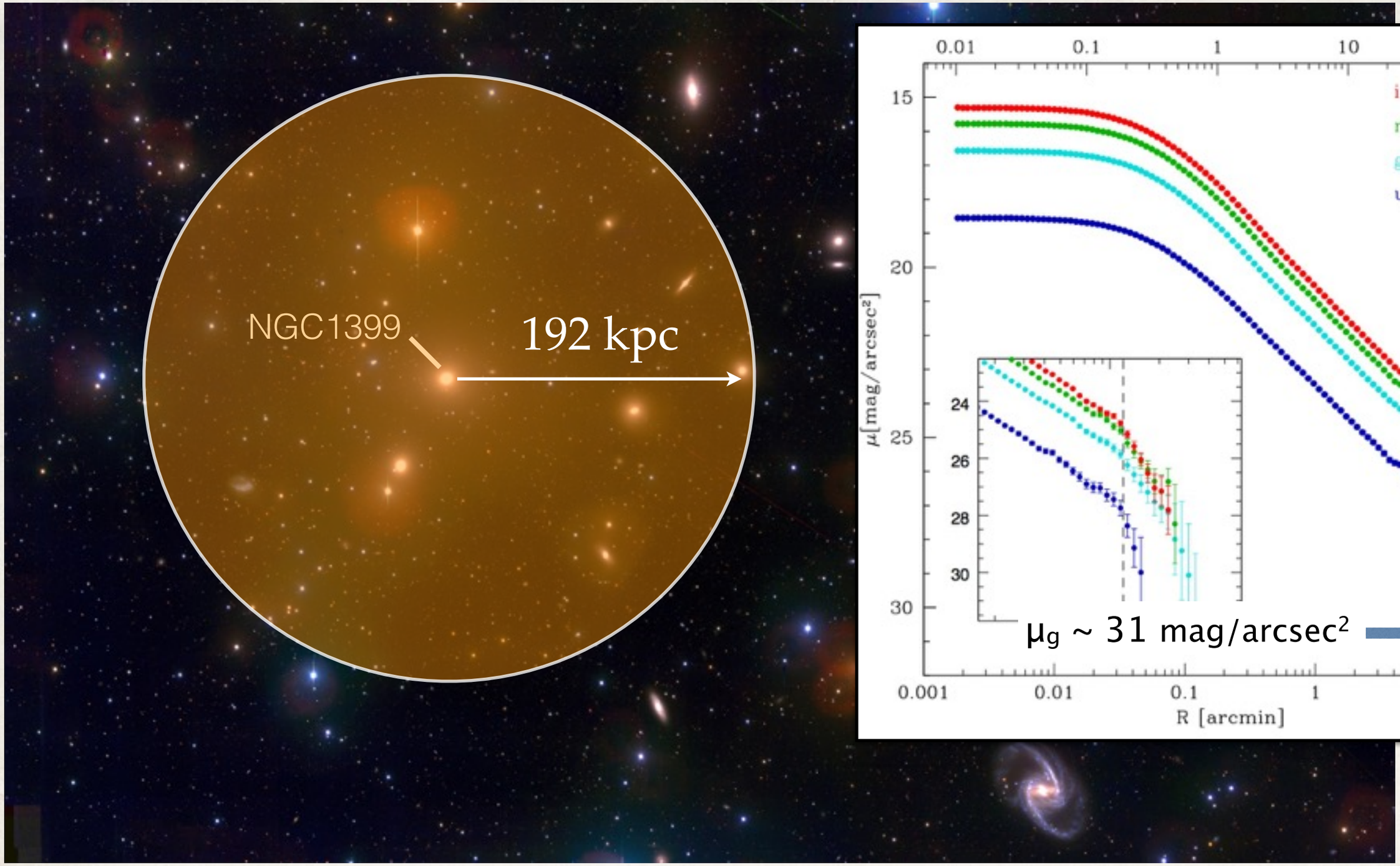

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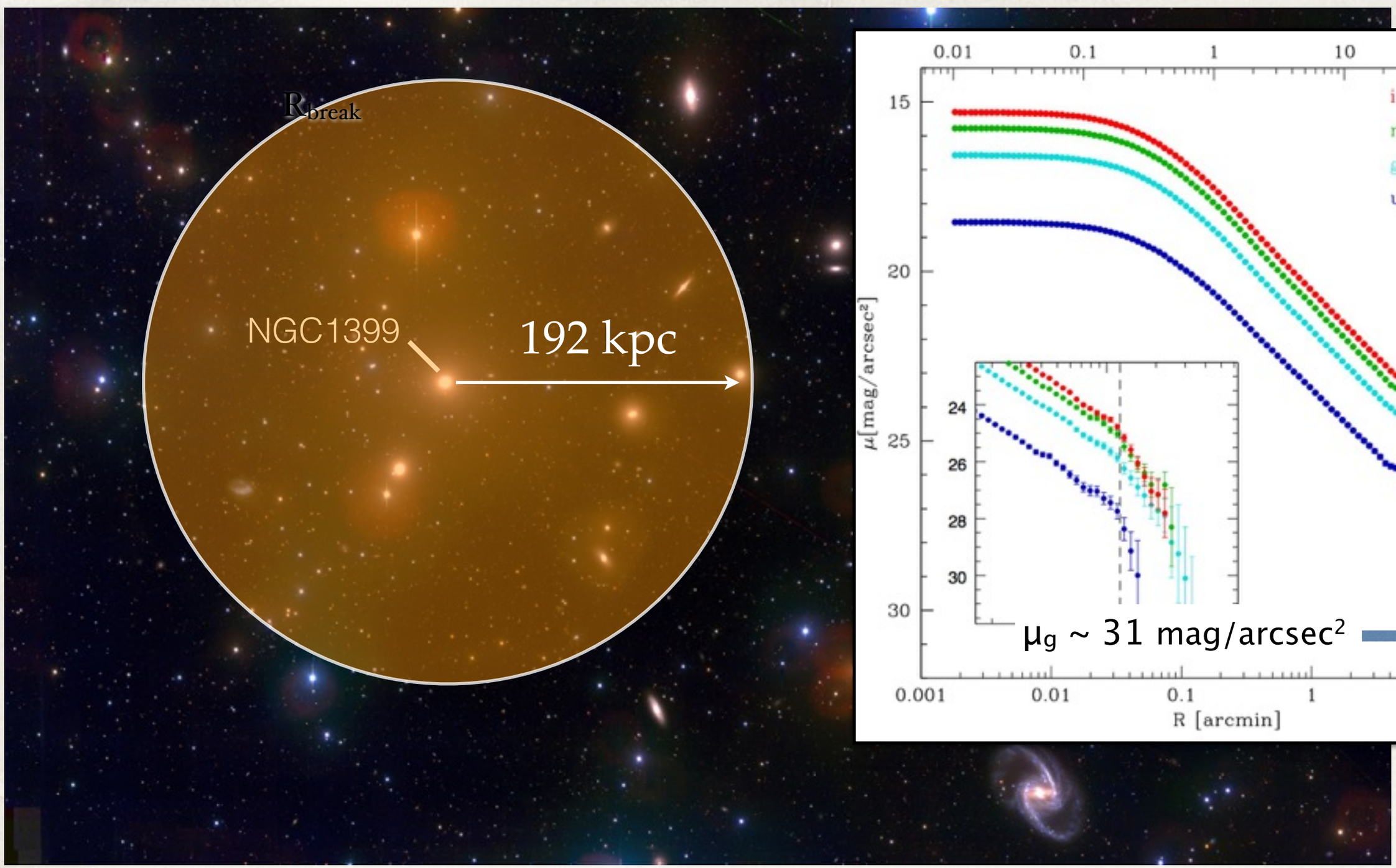

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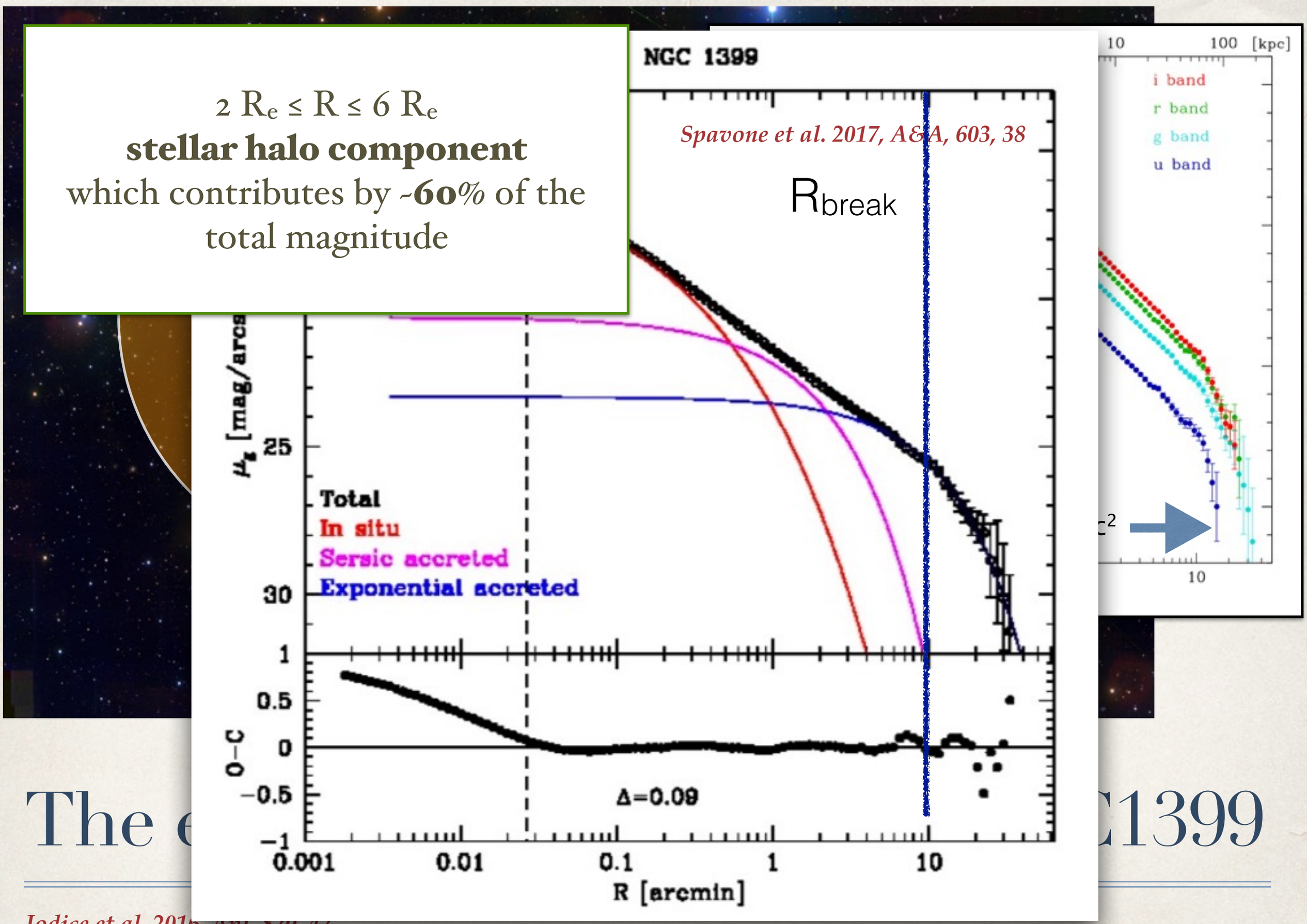
$2\ R_e \leq R \leq 6\ R_e$

stellar halo component

which contributes by ~**60**% of the total magnitude



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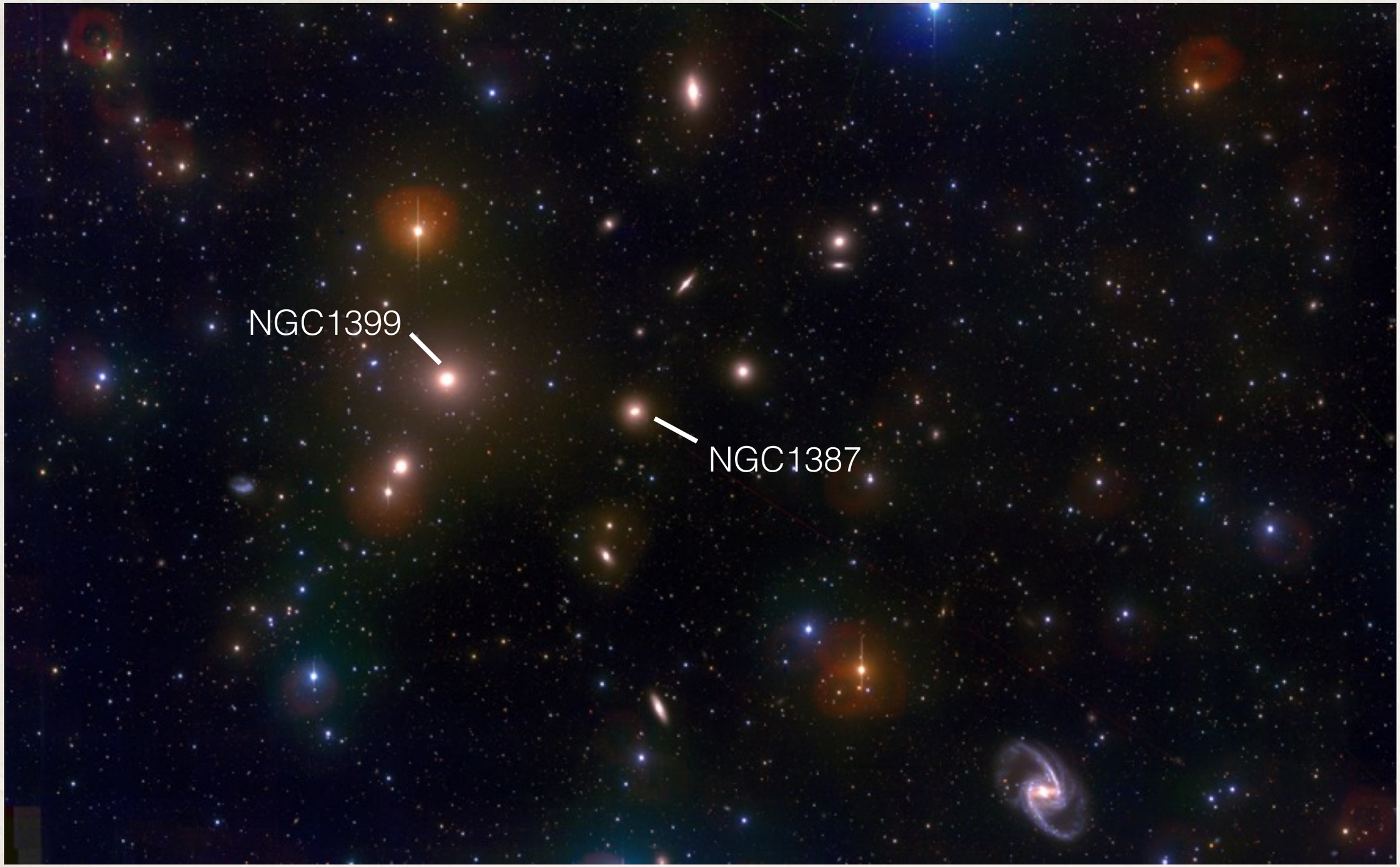

The intra-cluster regions: the stellar bridge between NGC1399 & NGC1387

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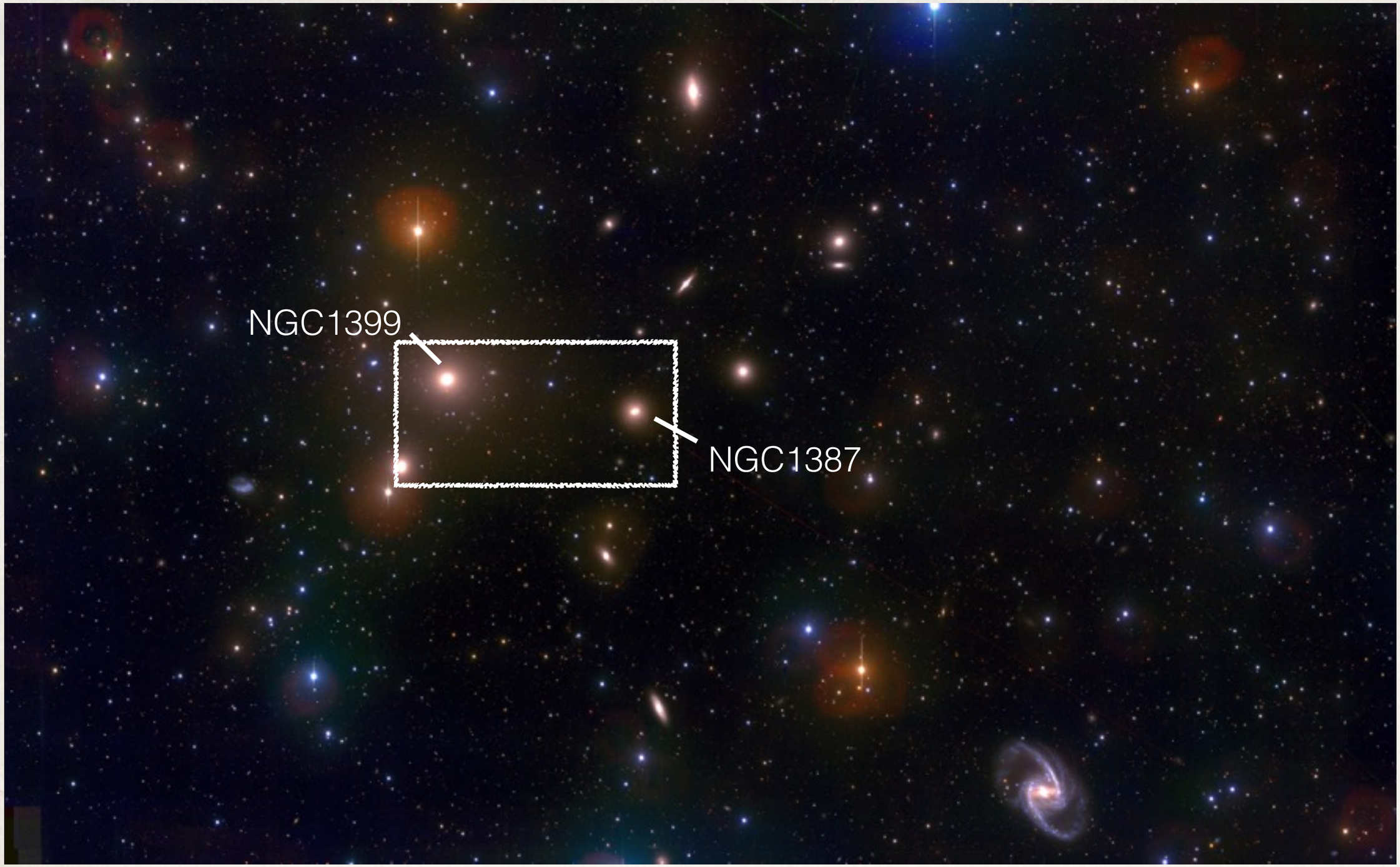

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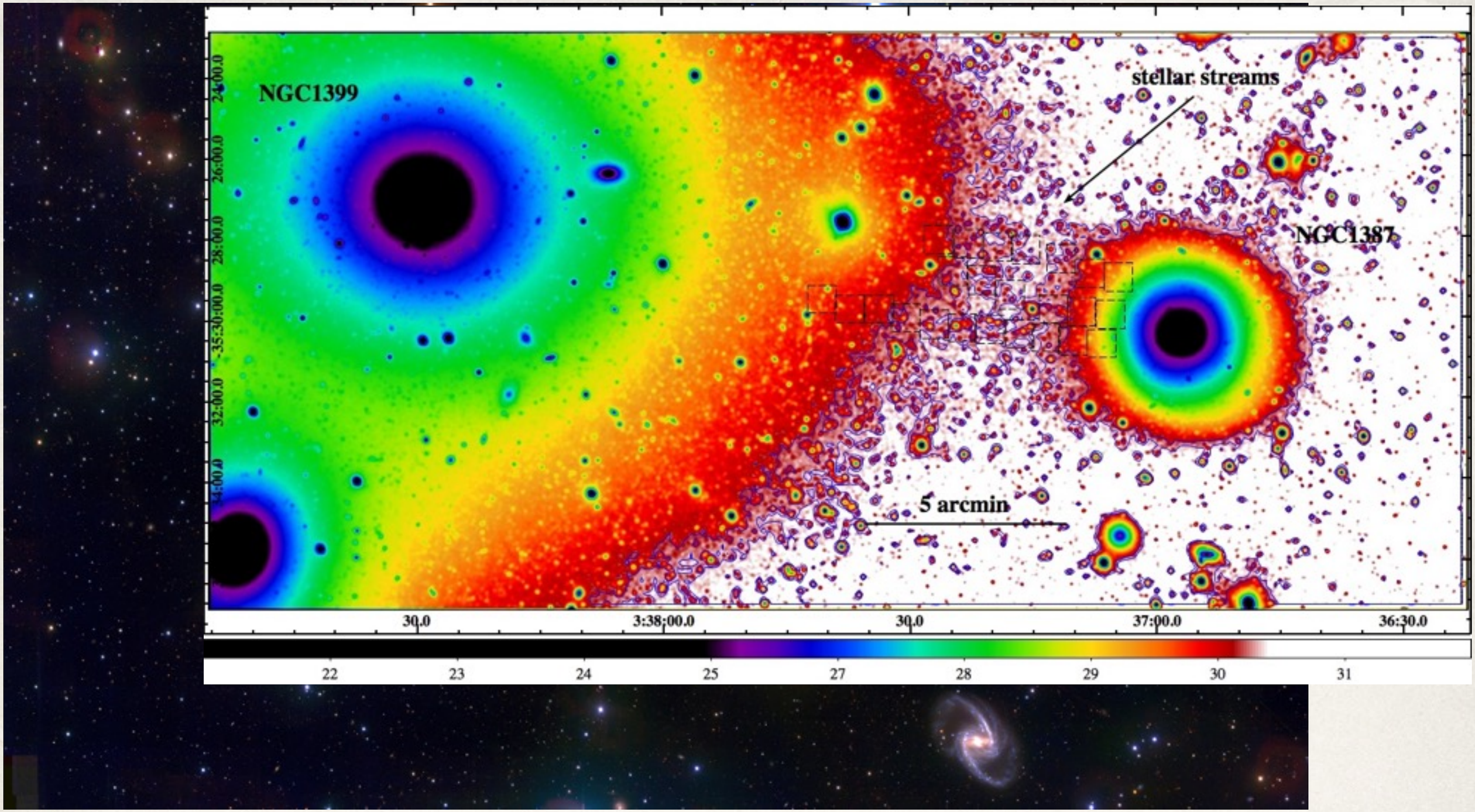

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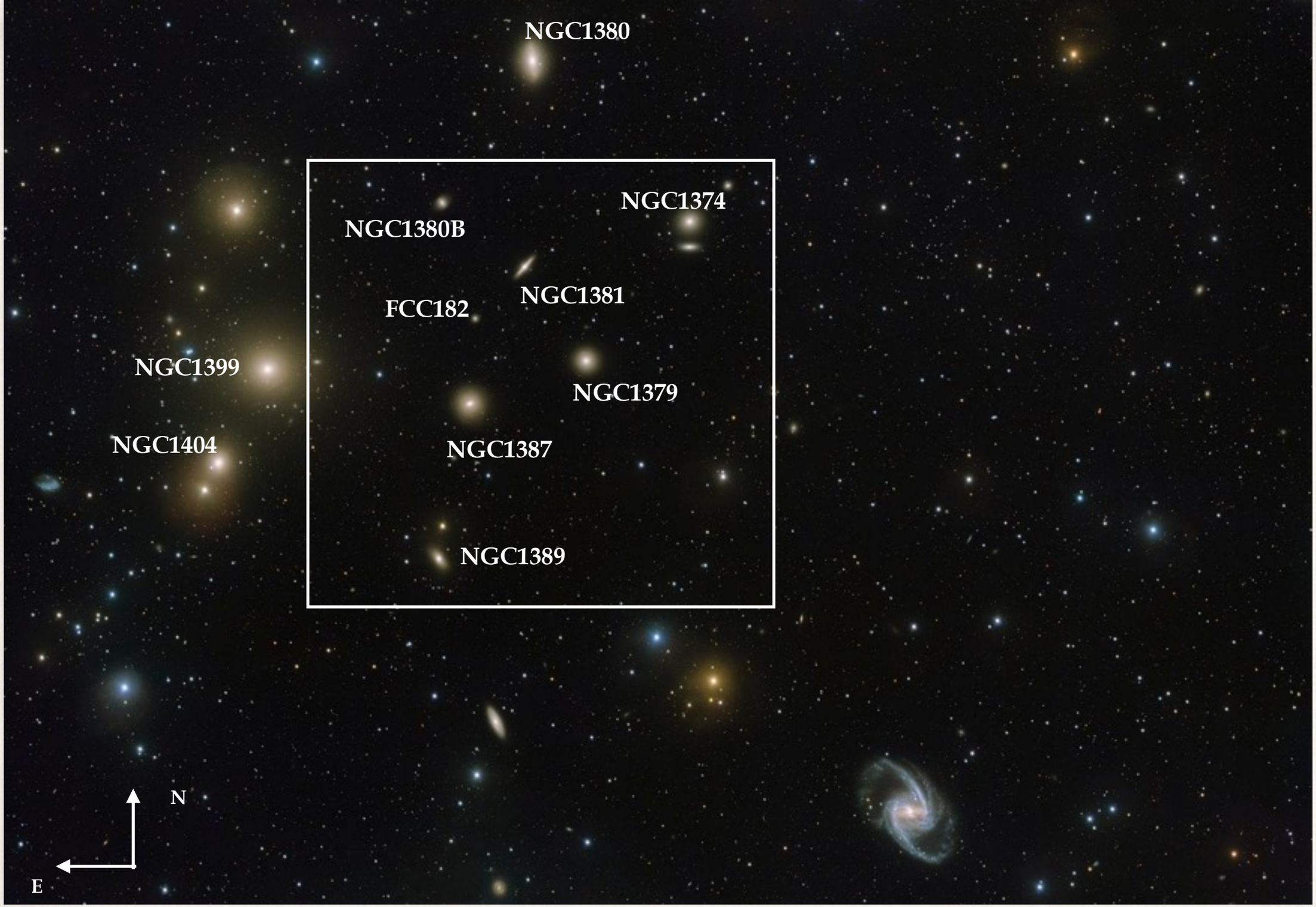
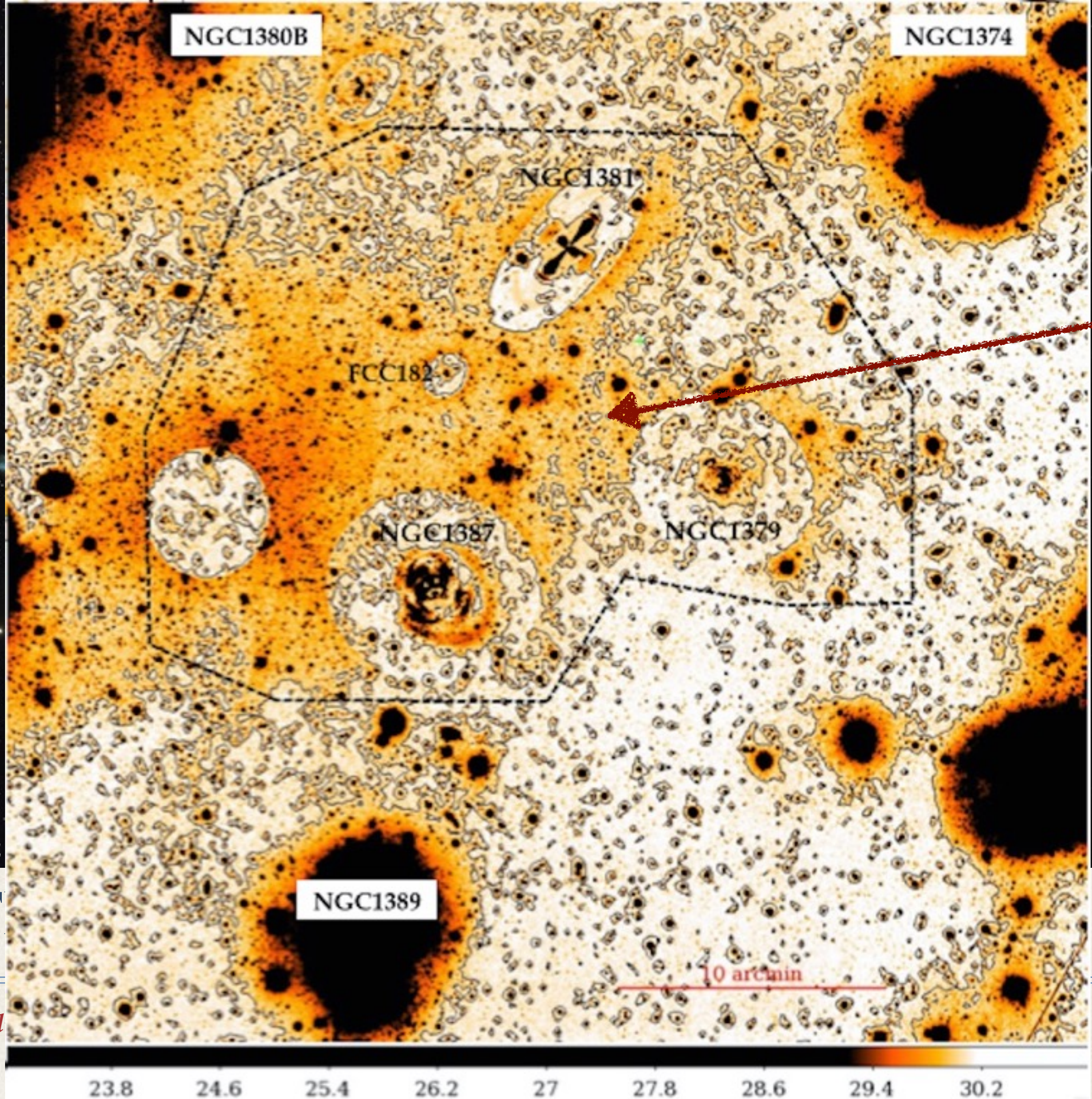


The intracluster regions: the ICL

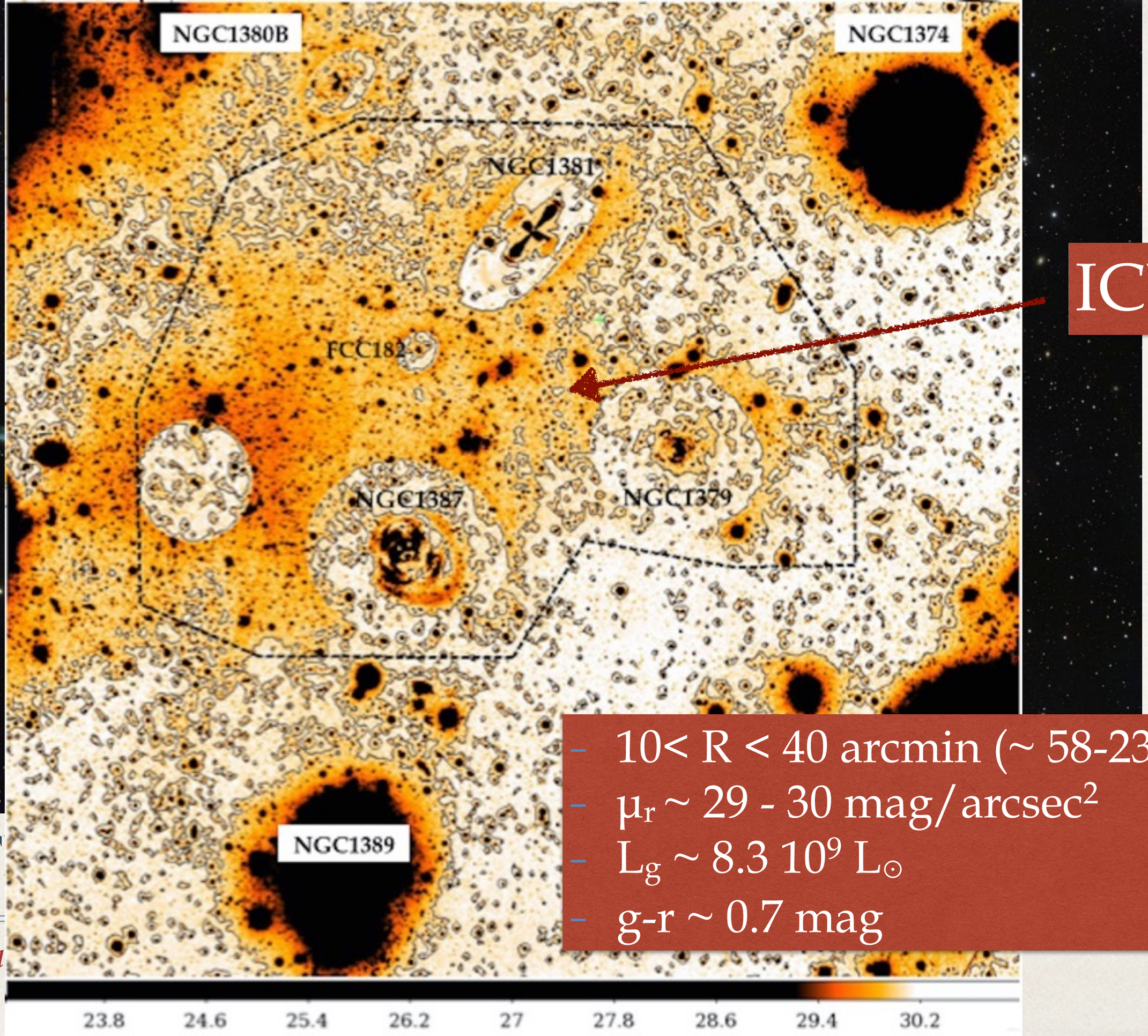
Iodice et al. 2017, ApJ, 851, 75


NGC1380B
NGC1374
NGC1381
FCC182
NGC1387
NGC1379
NGC1389
10 arcmin
23.8
24.6
25.4
26.2
27
27.8
28.6
29.4
30.2

ICL

T

Iod

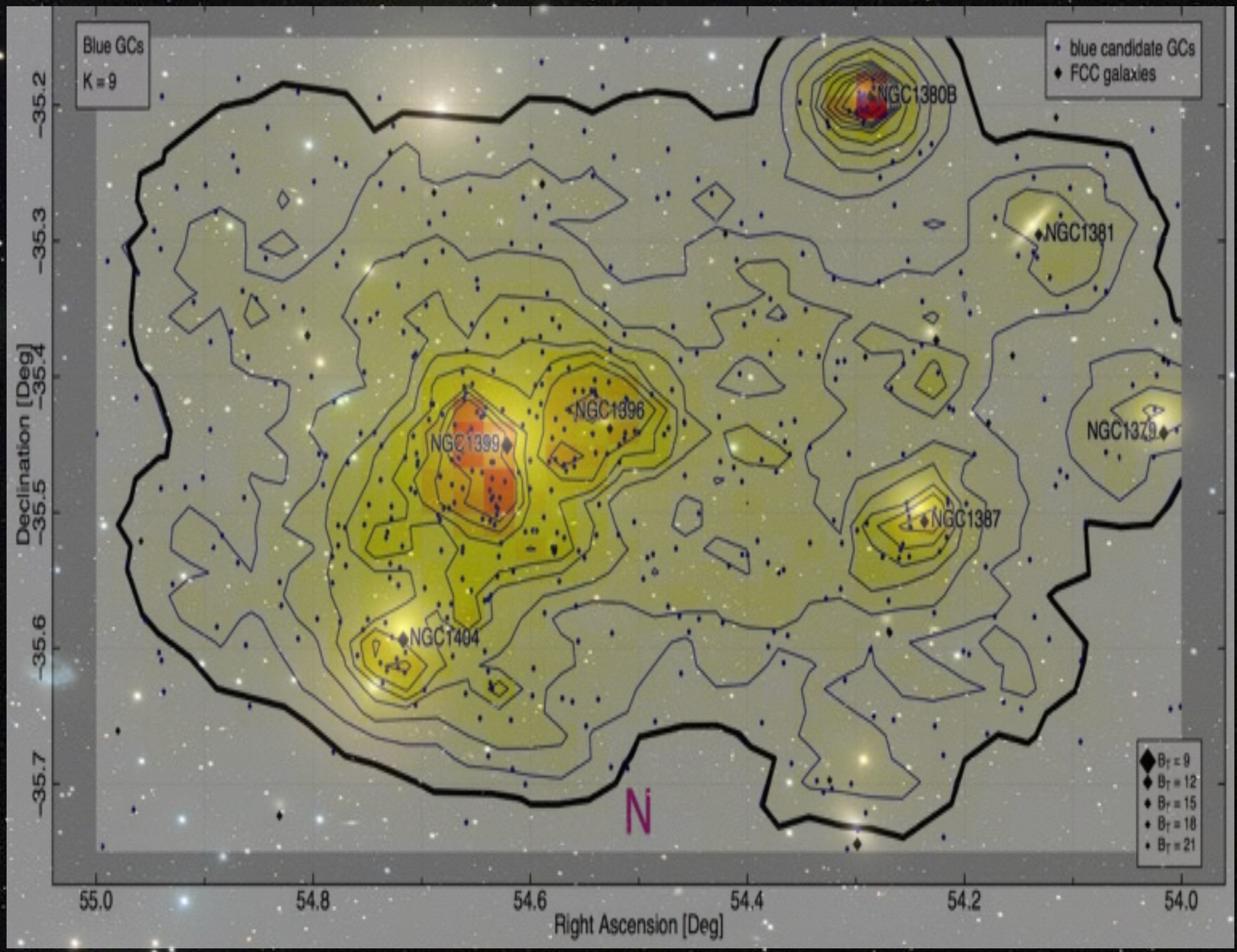


ICL

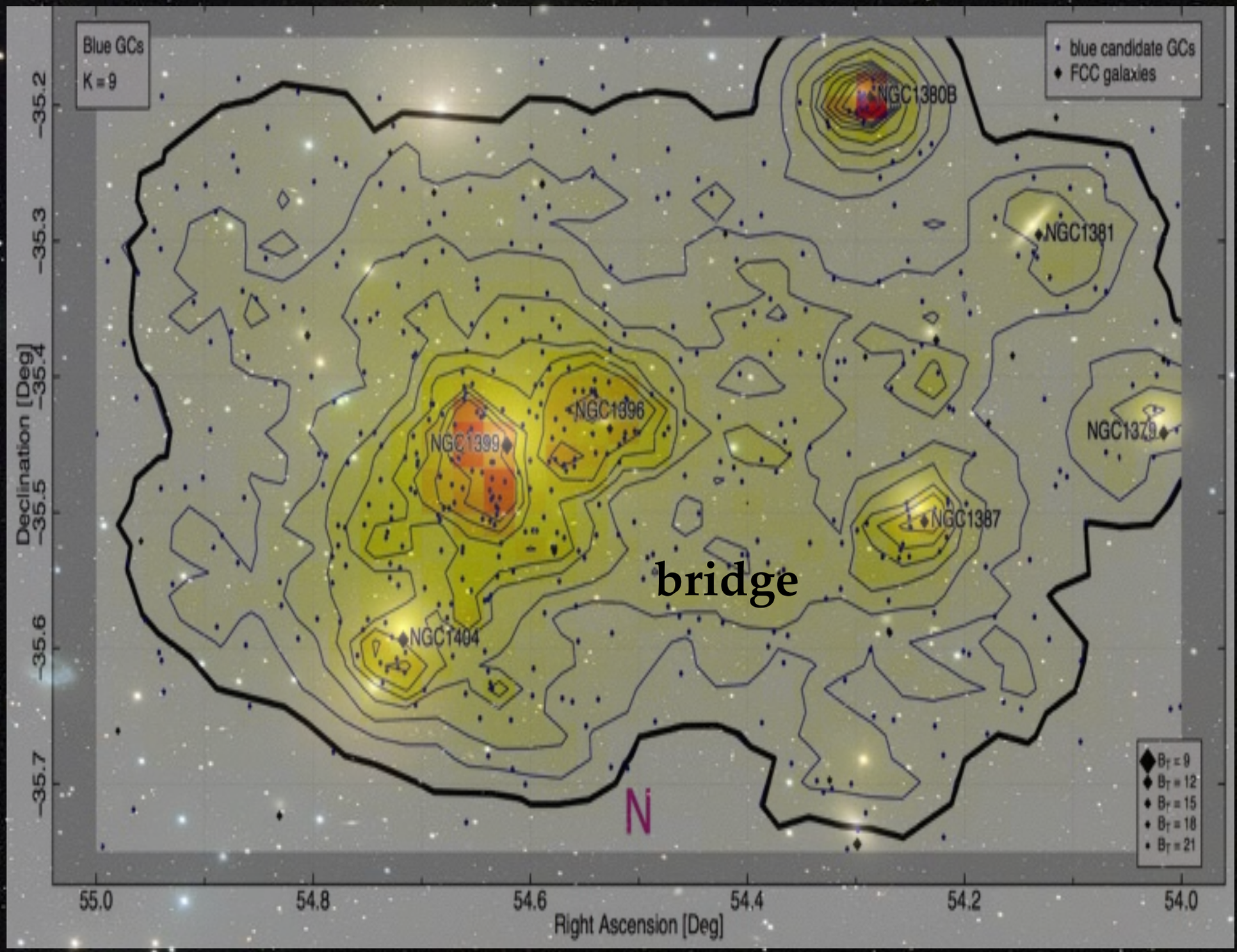
- 10< R < 40 arcmin (~ 58-230 kpc)
- μ_r ~ 29 - 30 mag/arcsec^2
- L_g ~ 8.3 10^9 $L_\odot$
- g-r ~ 0.7 mag

T

Iod



D'Abrusco et al. 2016



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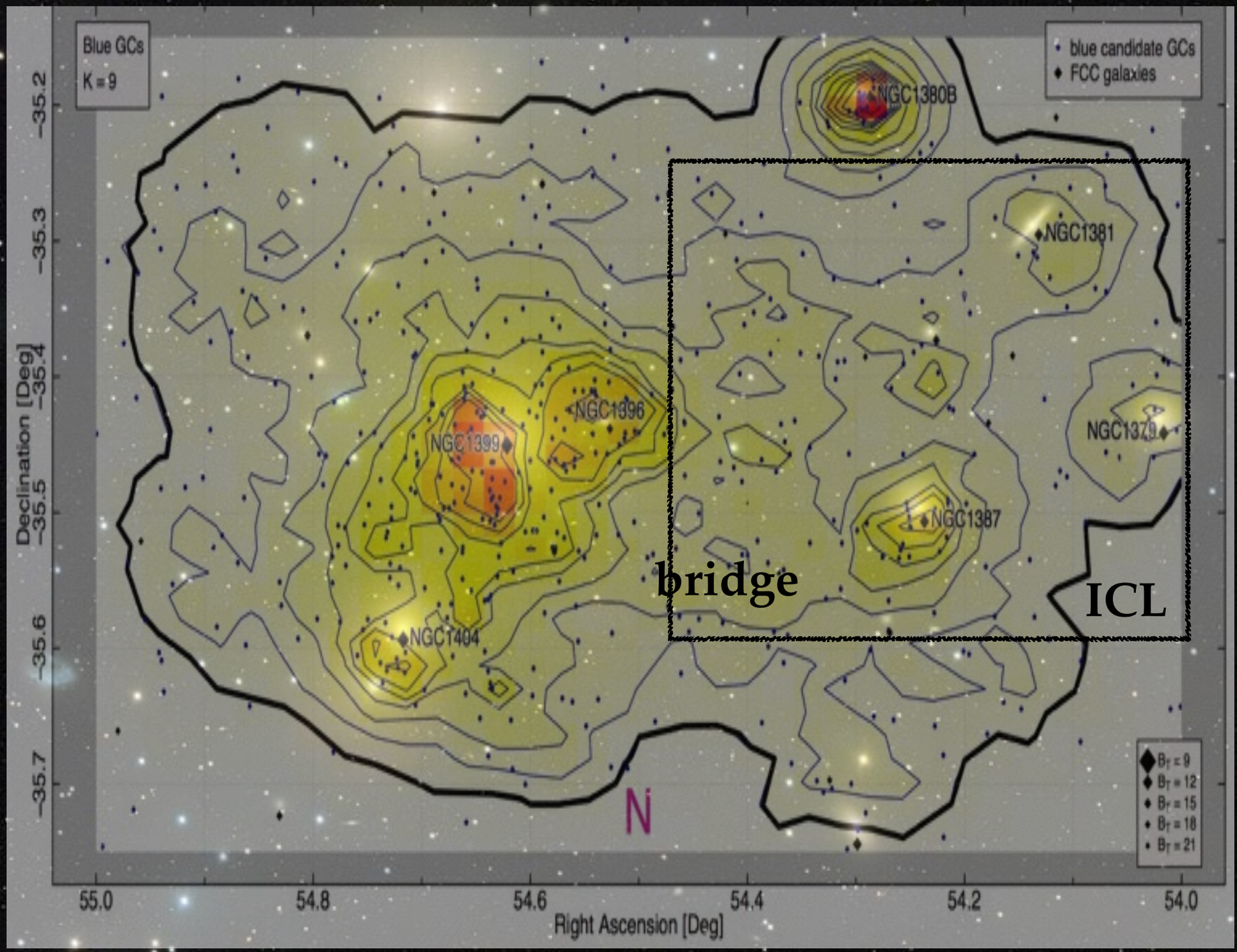
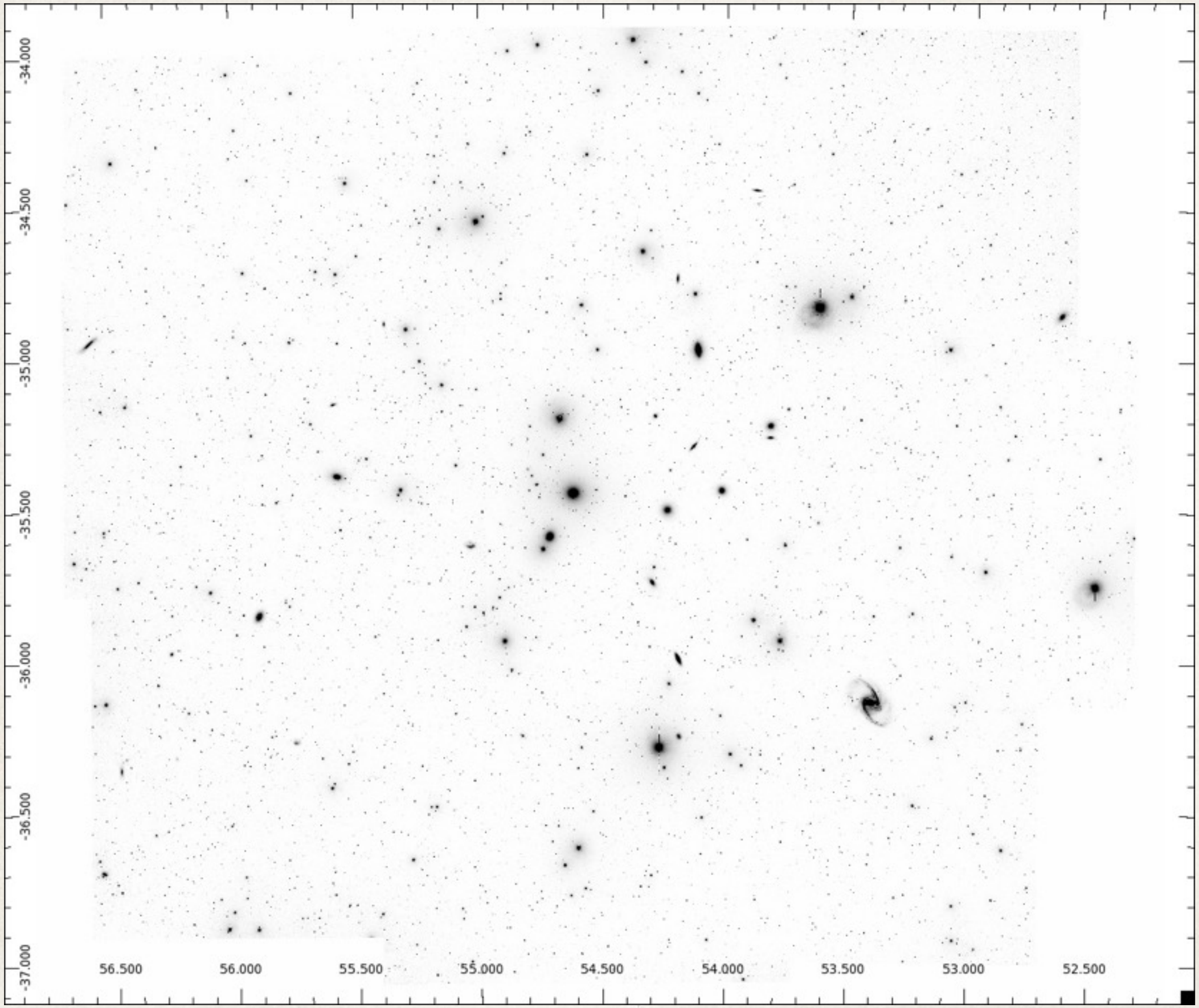


D'Abrusco et al. 2016

The bright ETGs in the R_{vir} of the cluster: RESULTS



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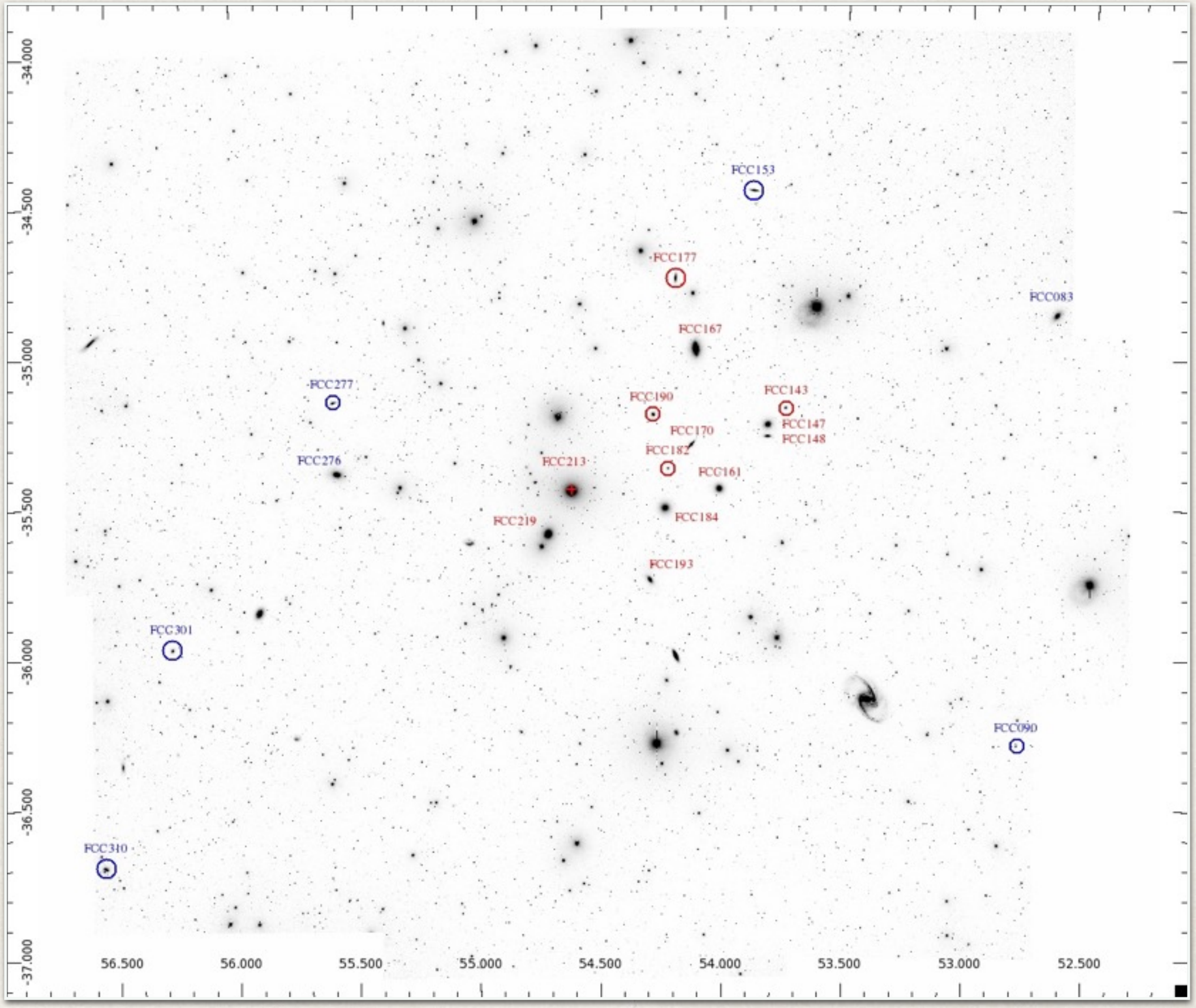
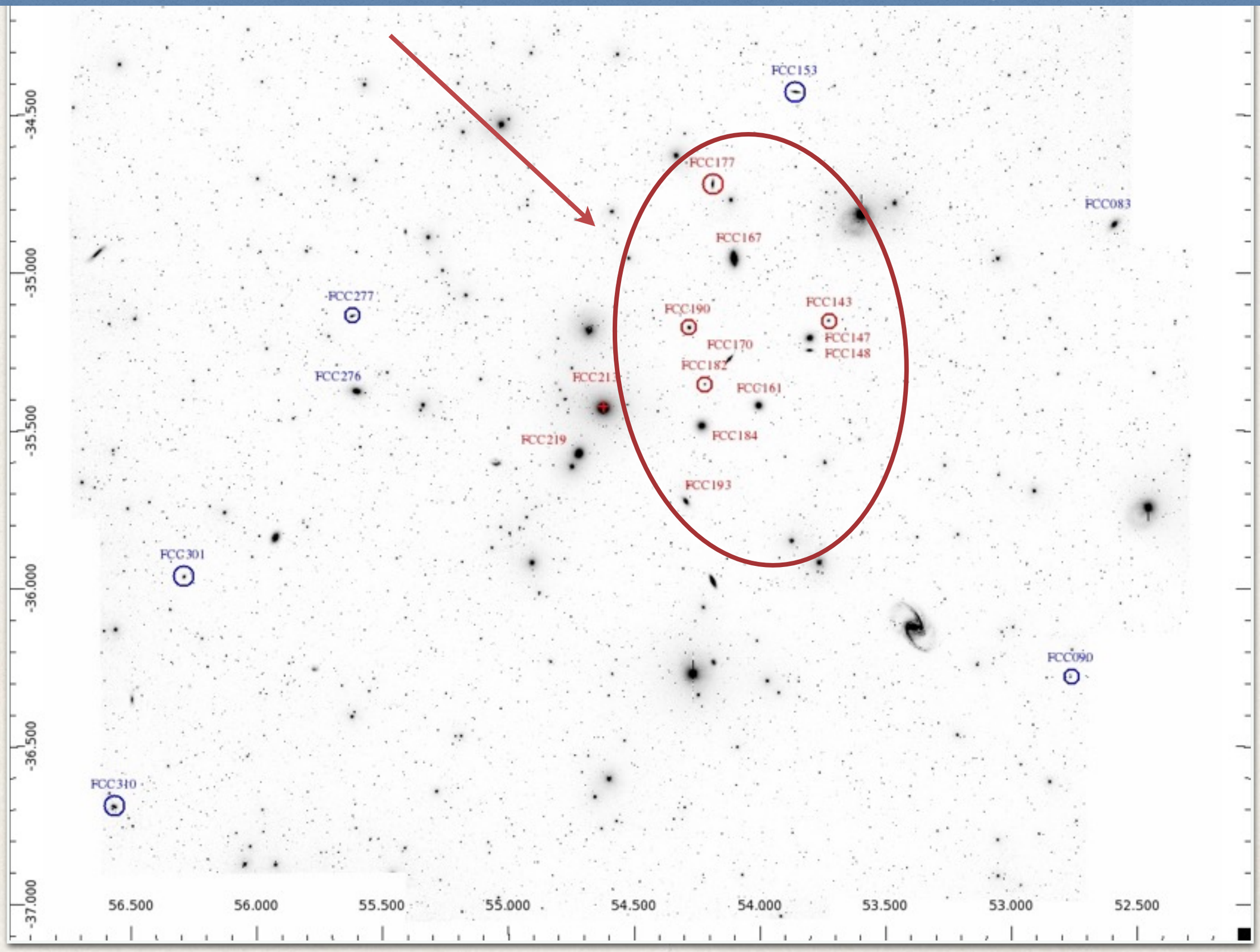


the bulk of the gravitational interactions between galaxies should have happened on the W-NW side of the cluster, where most of the bright ETGs are located and where the intra-cluster baryons are found



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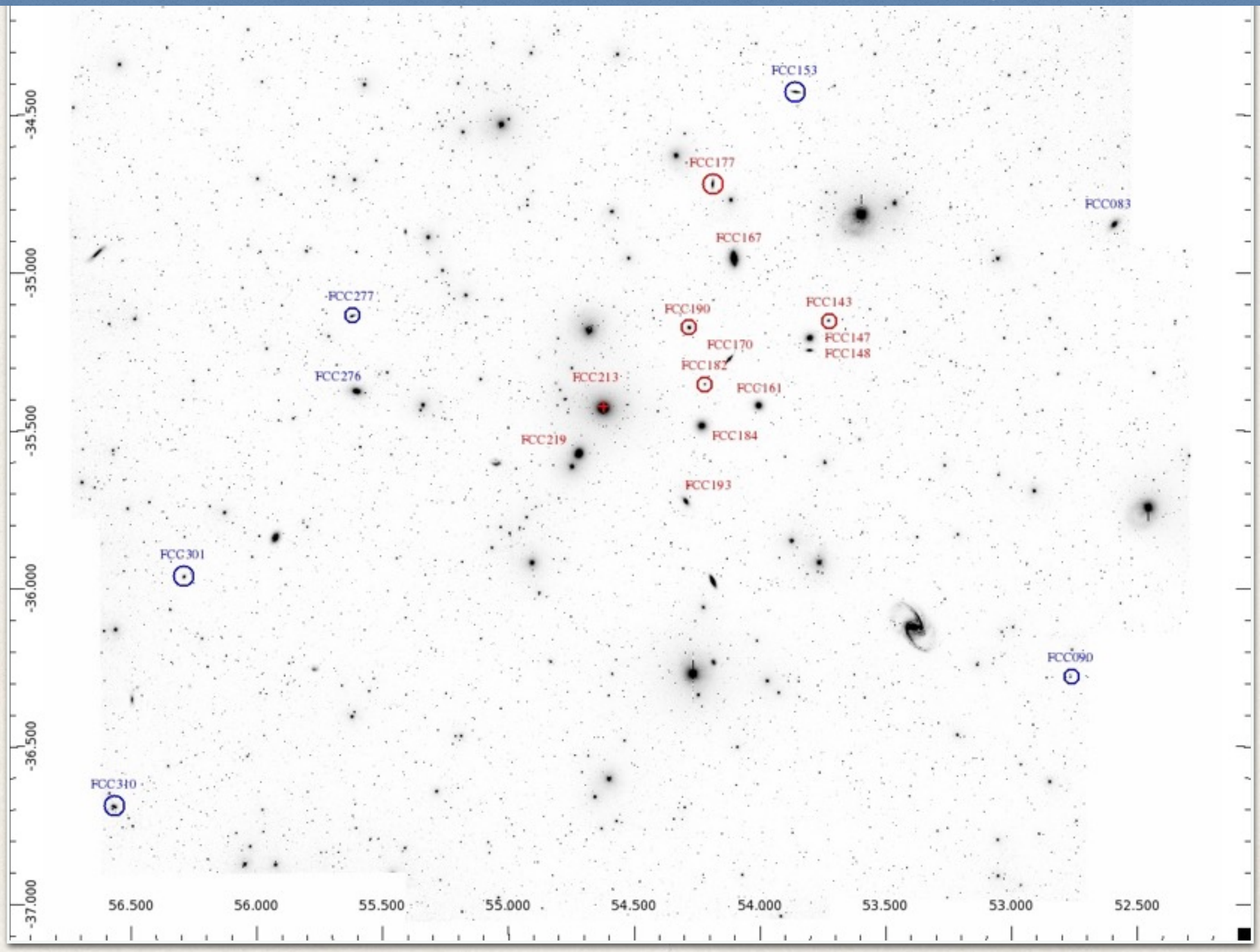

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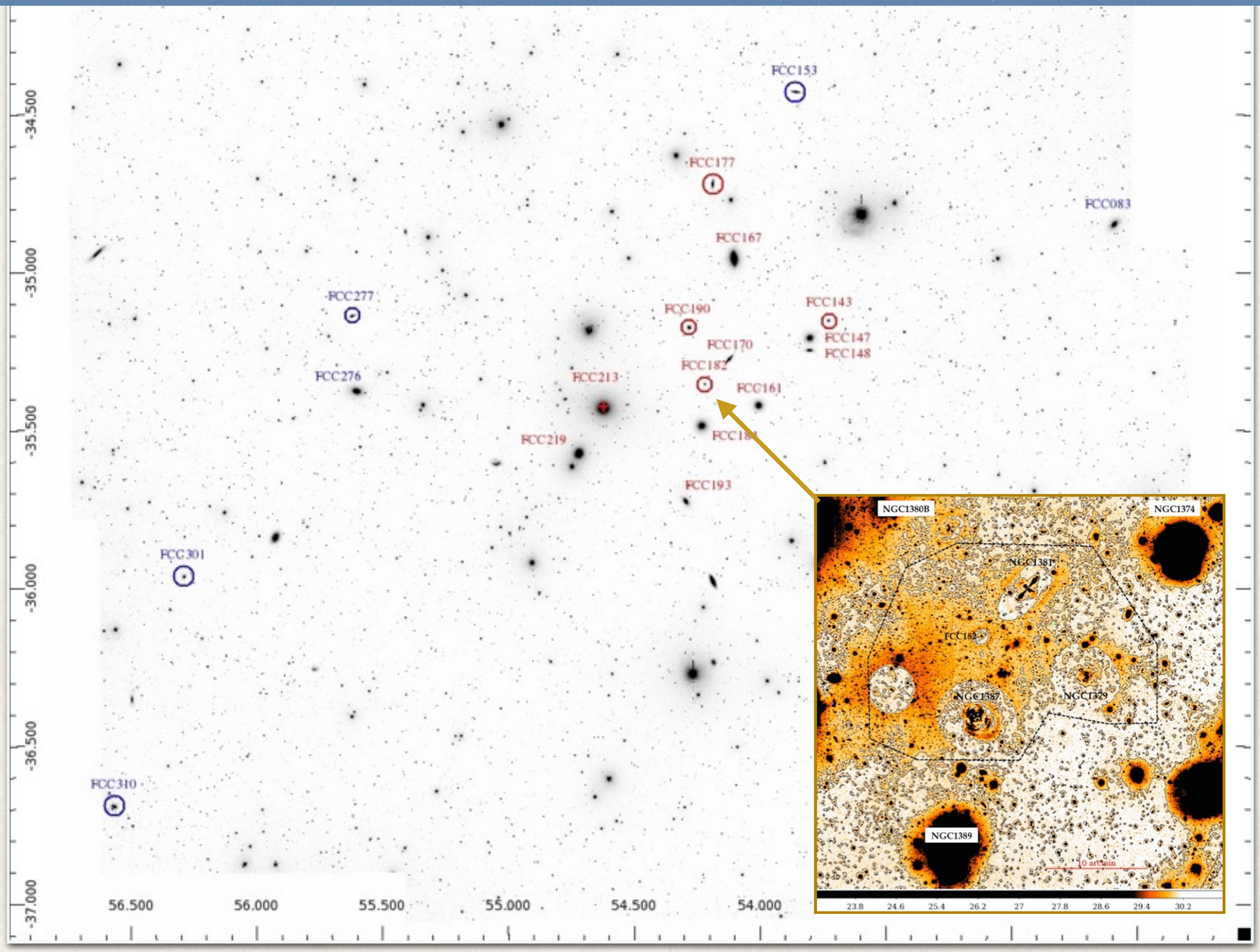

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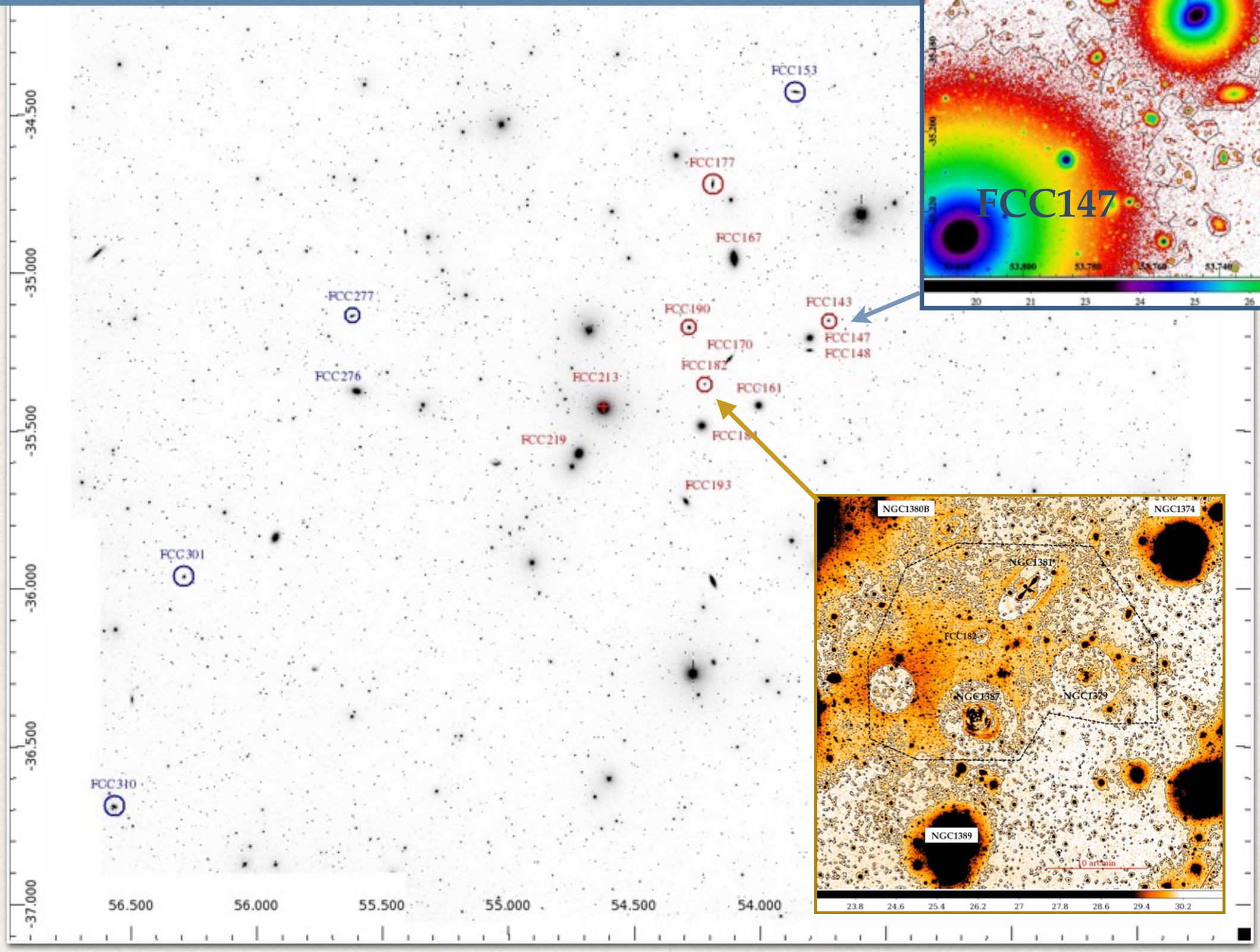

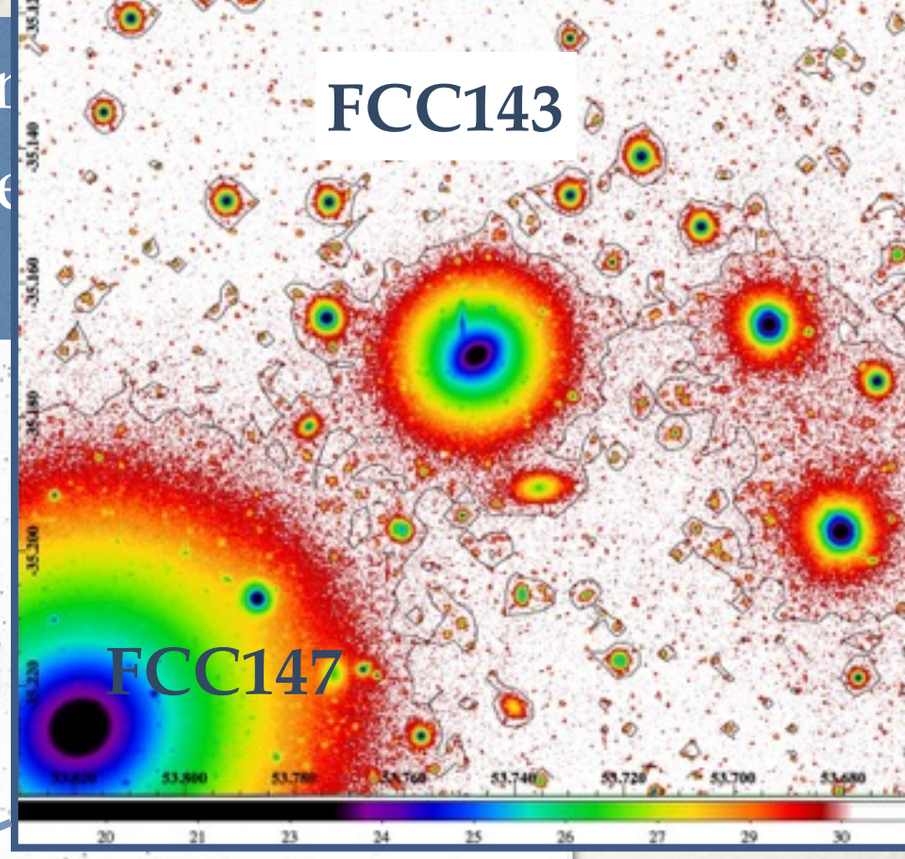

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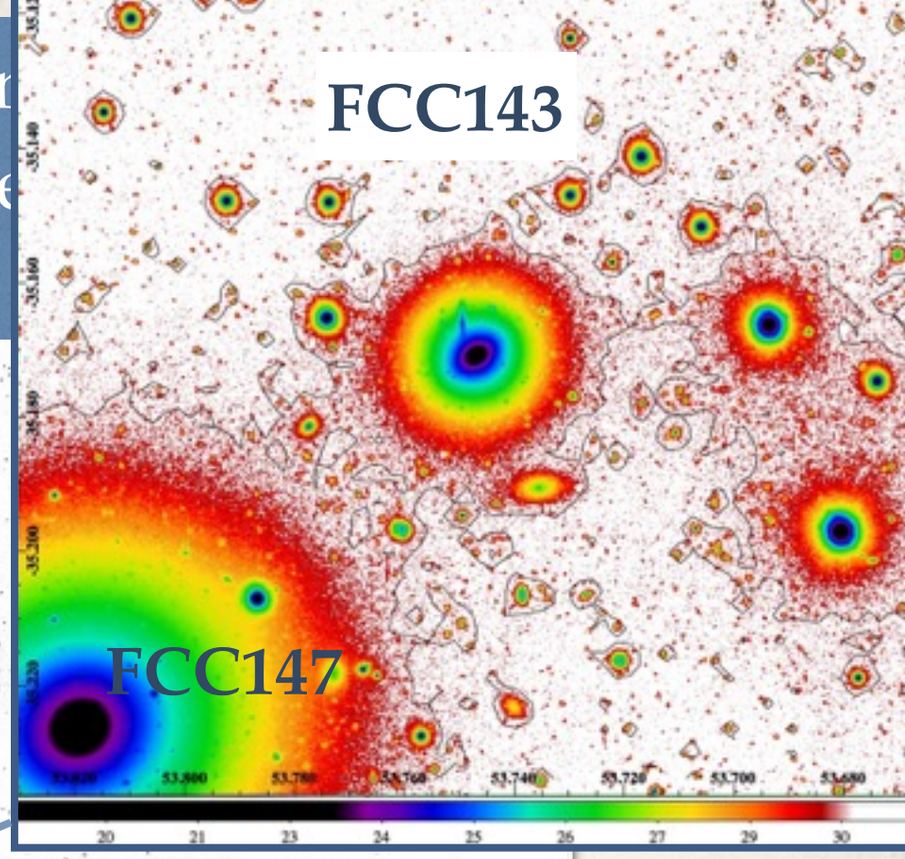

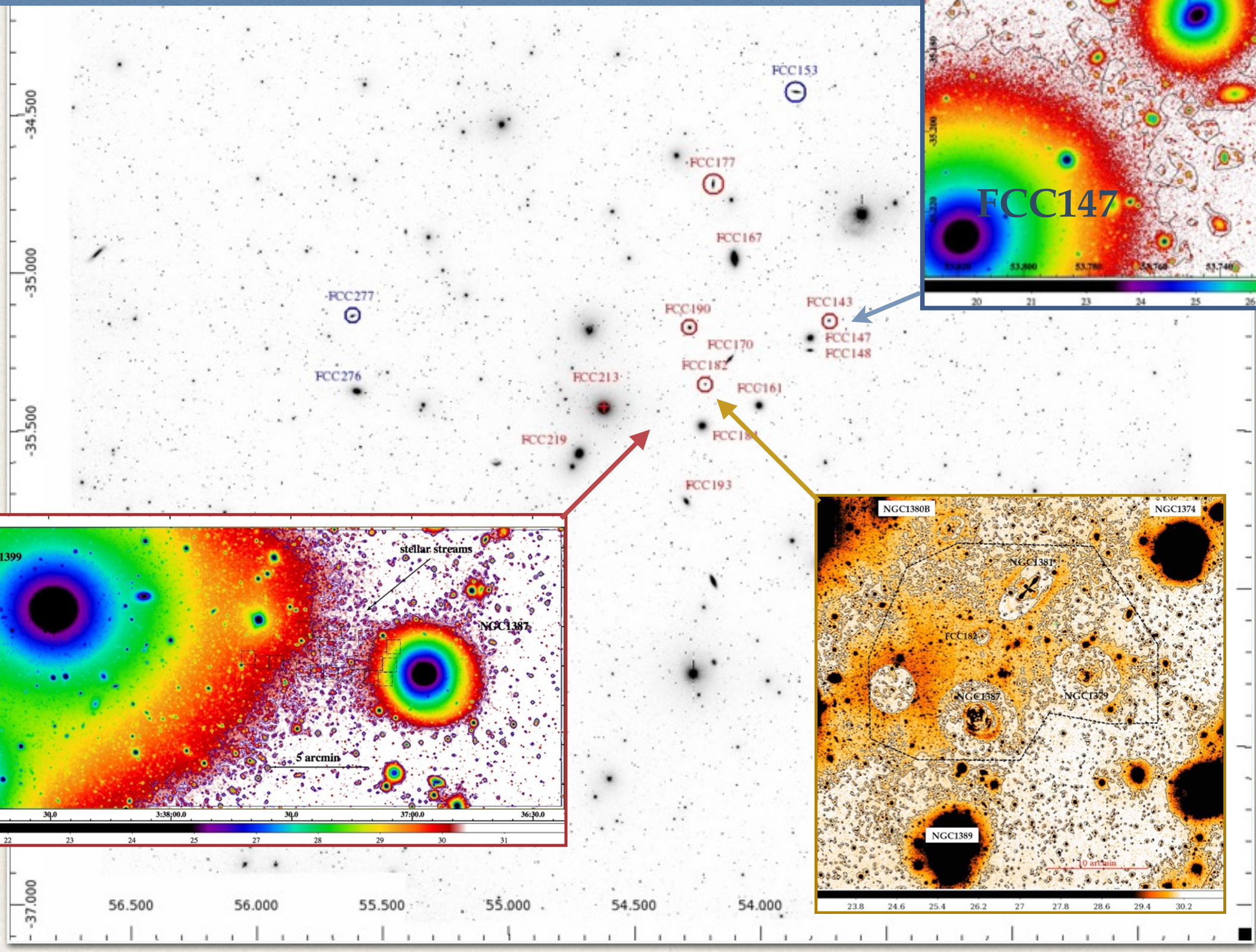

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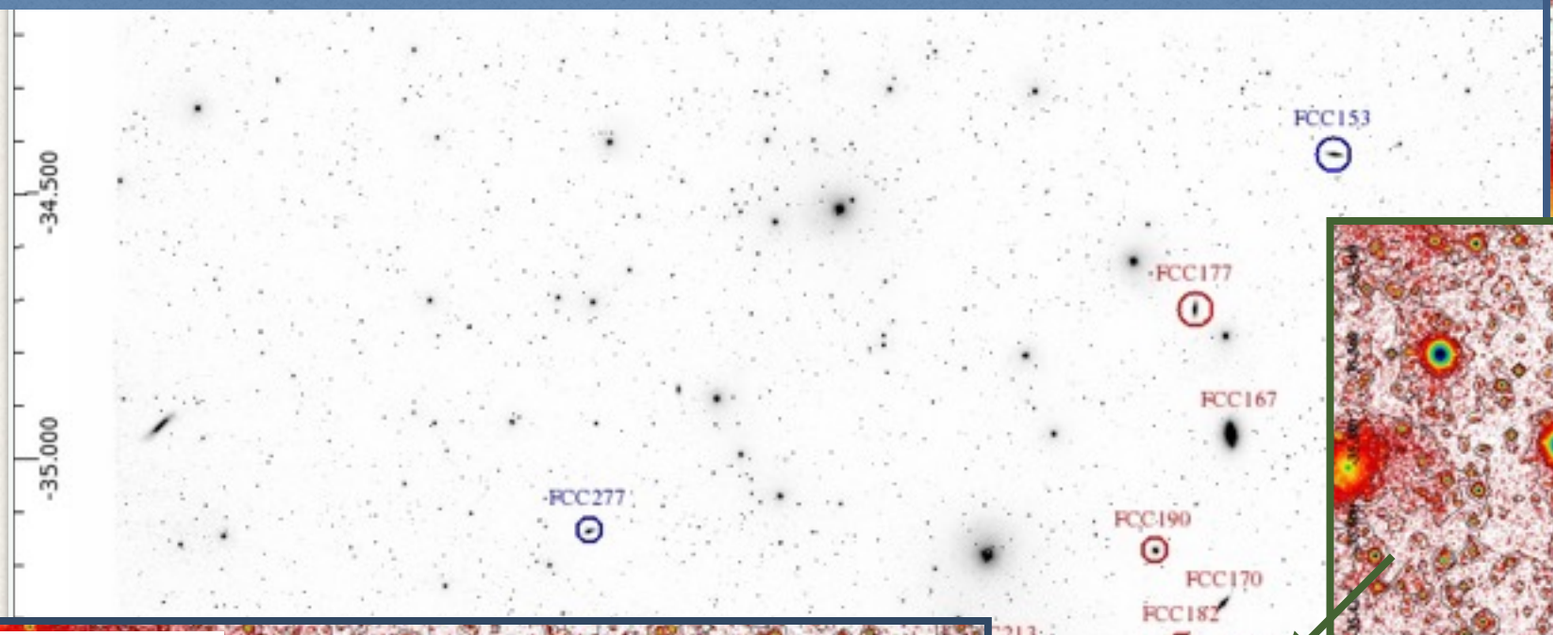
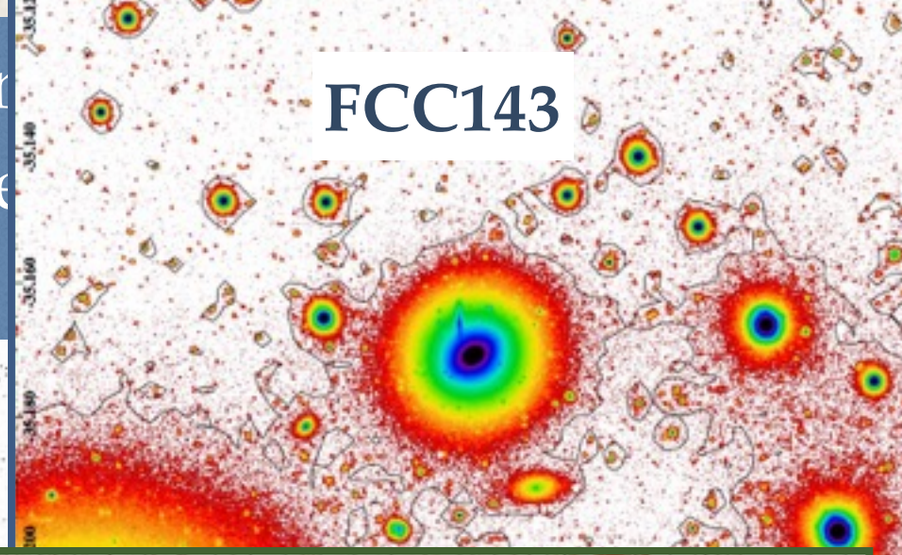
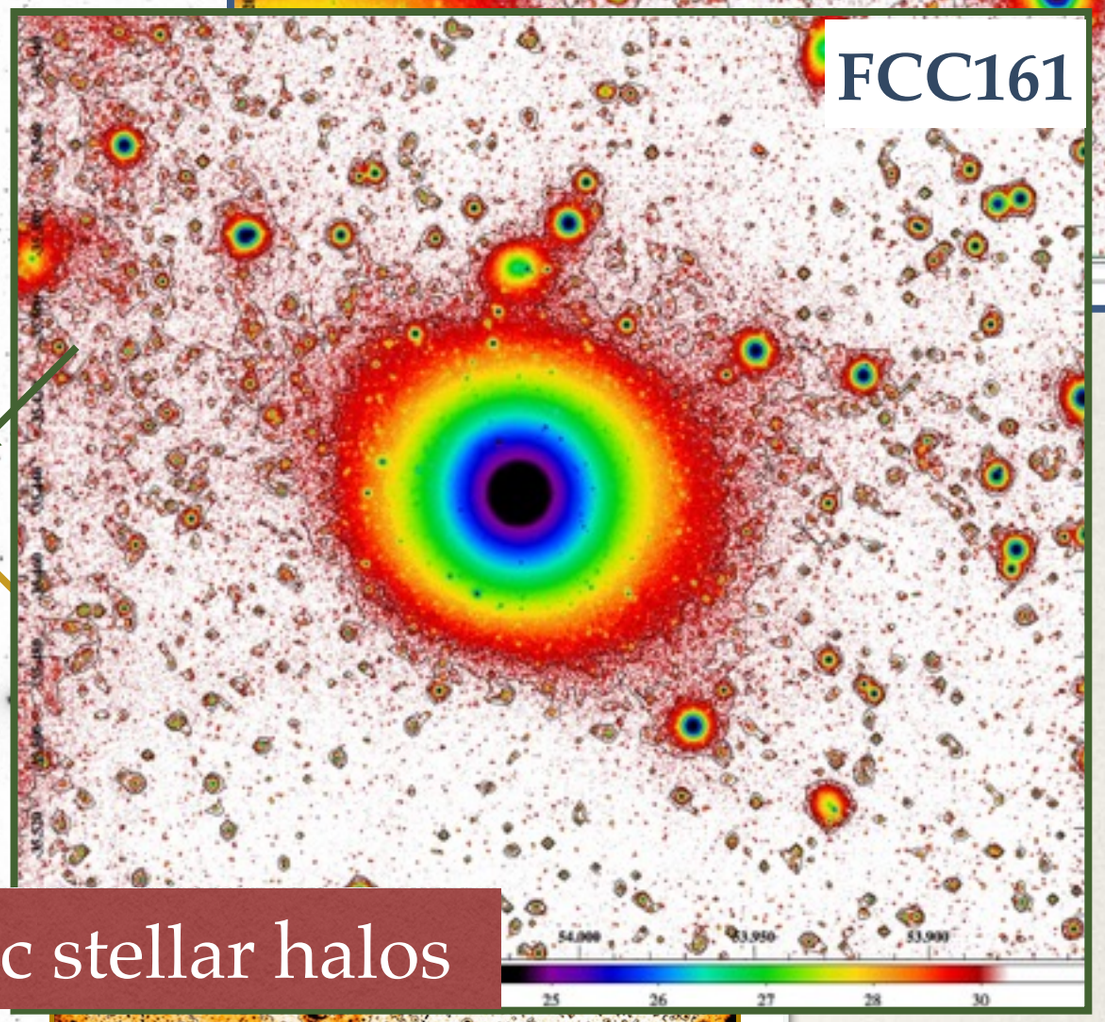
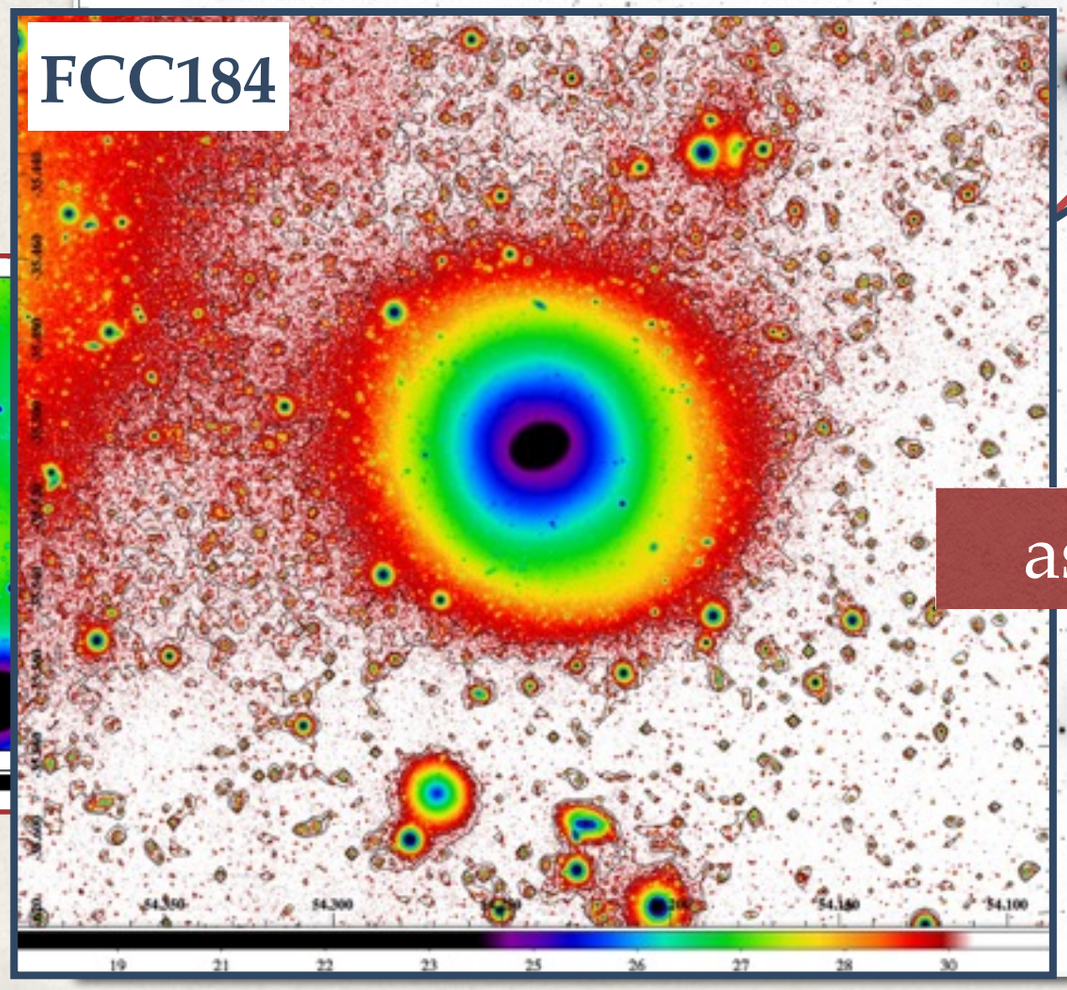
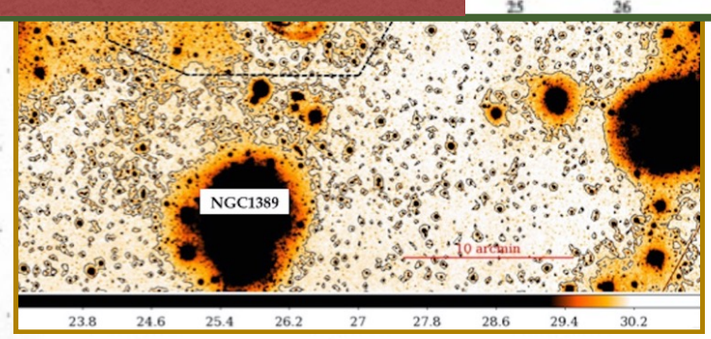


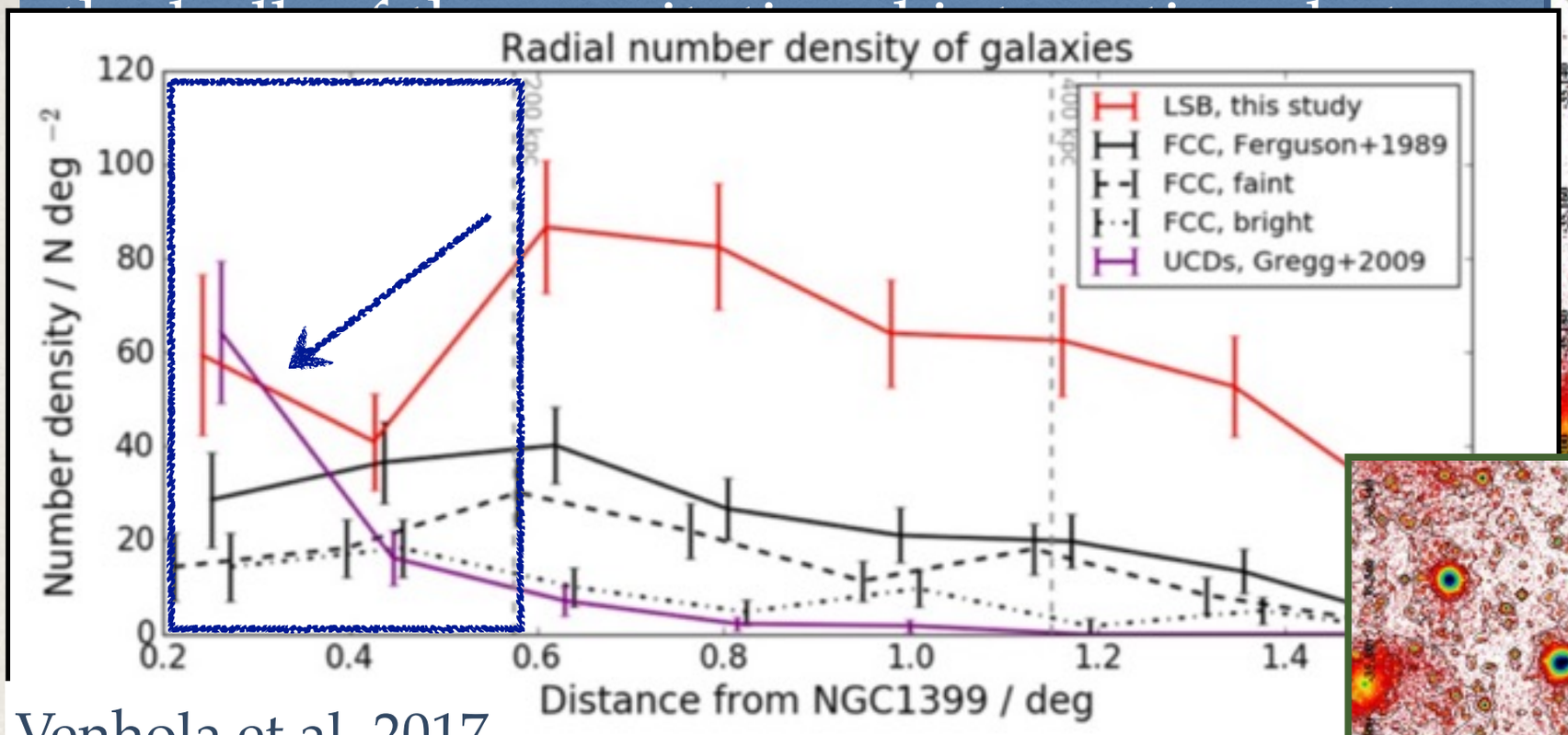




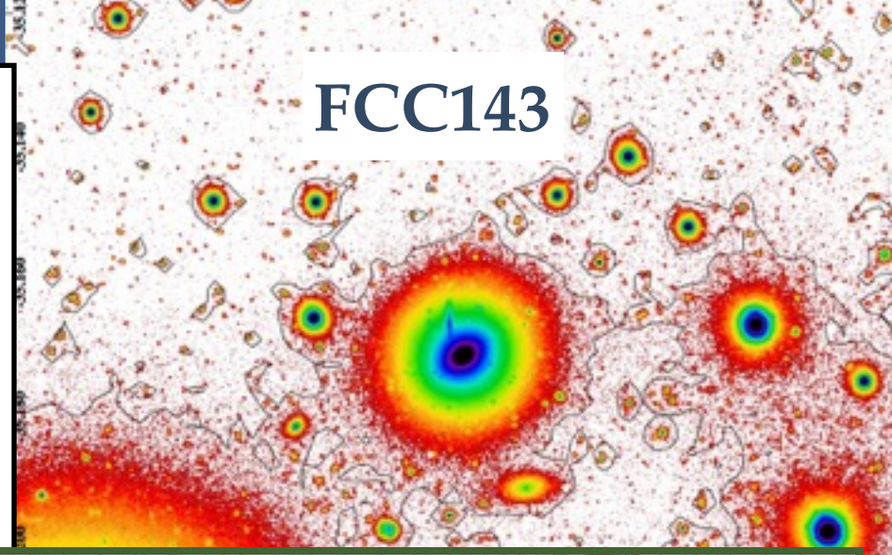


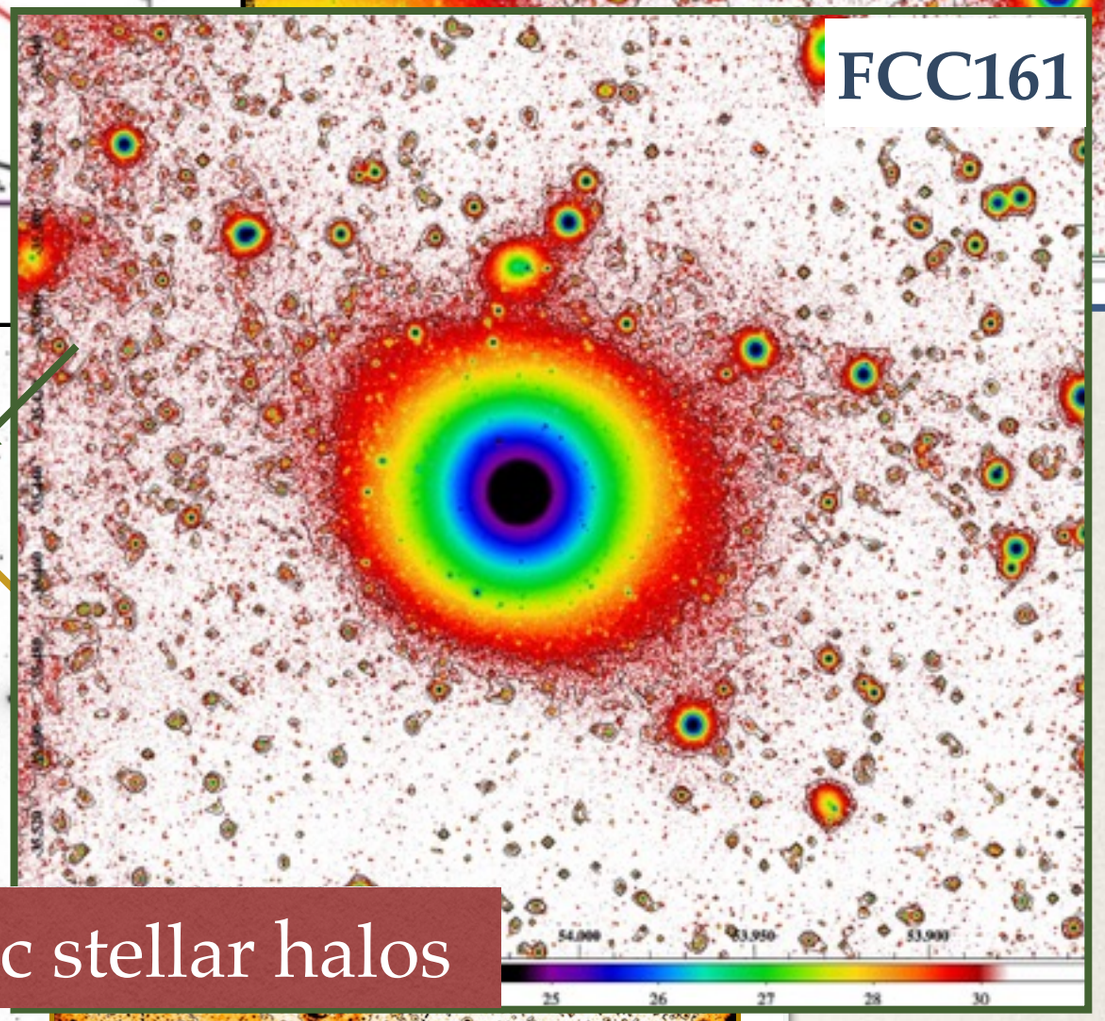
asymmetric stellar halos

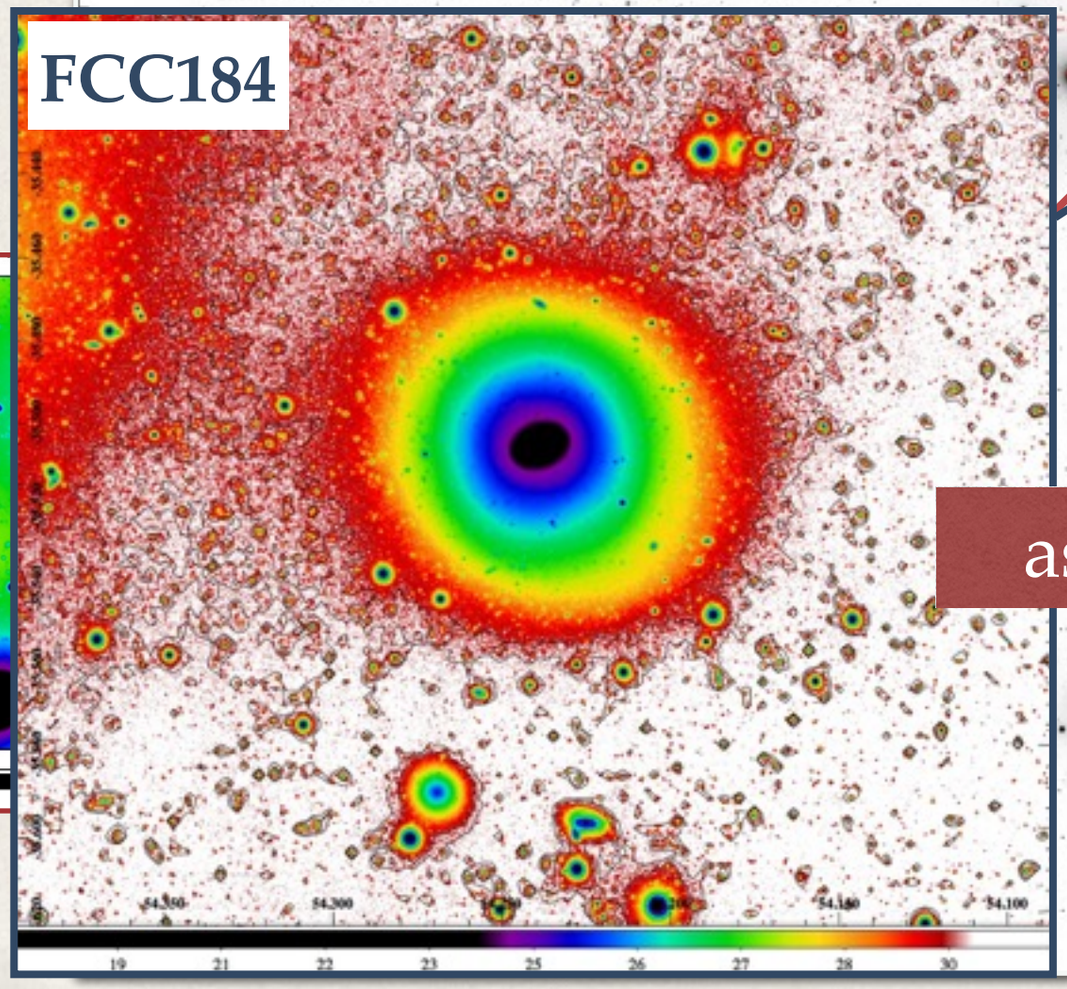


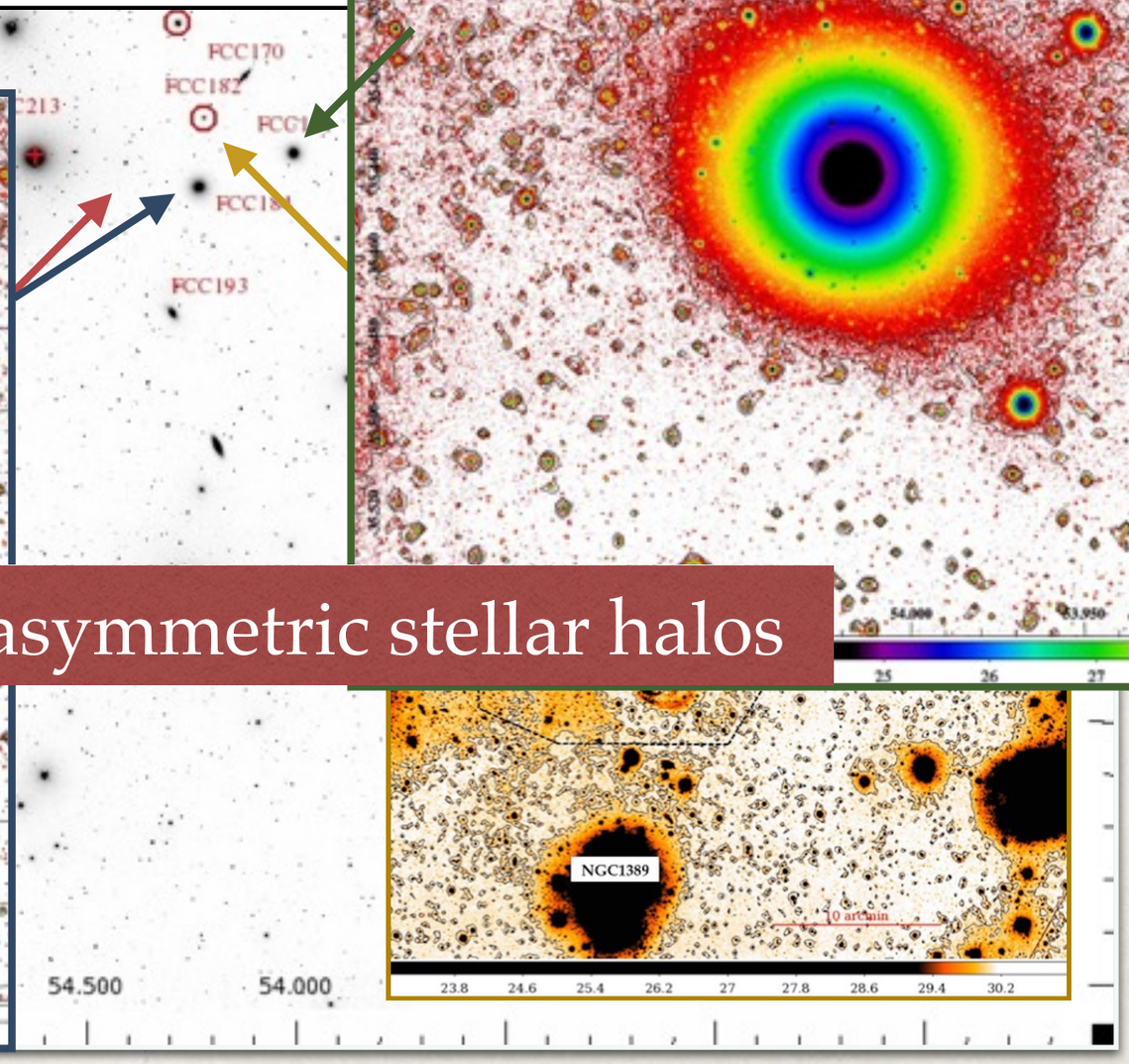


Venhola et al. 2017

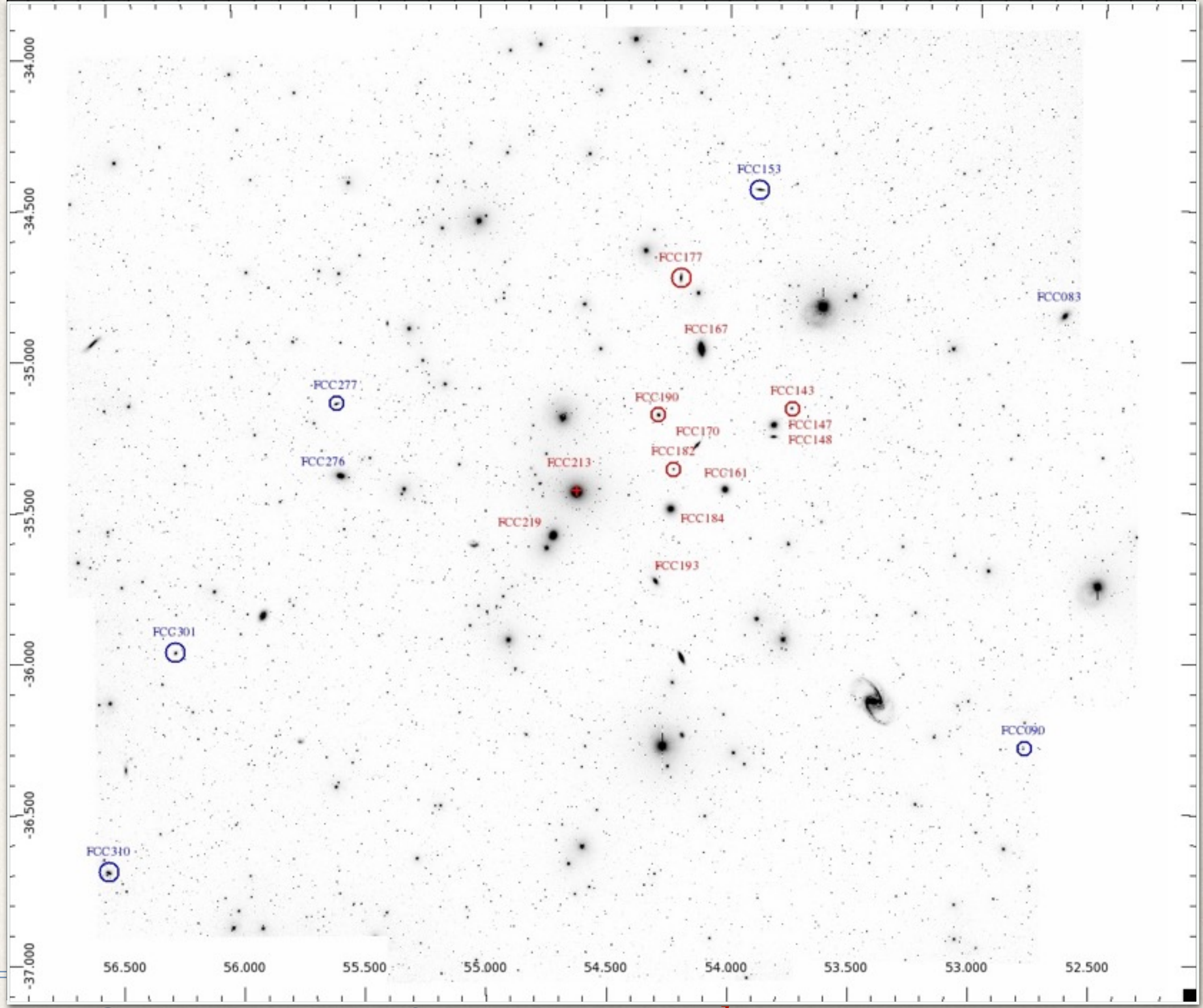






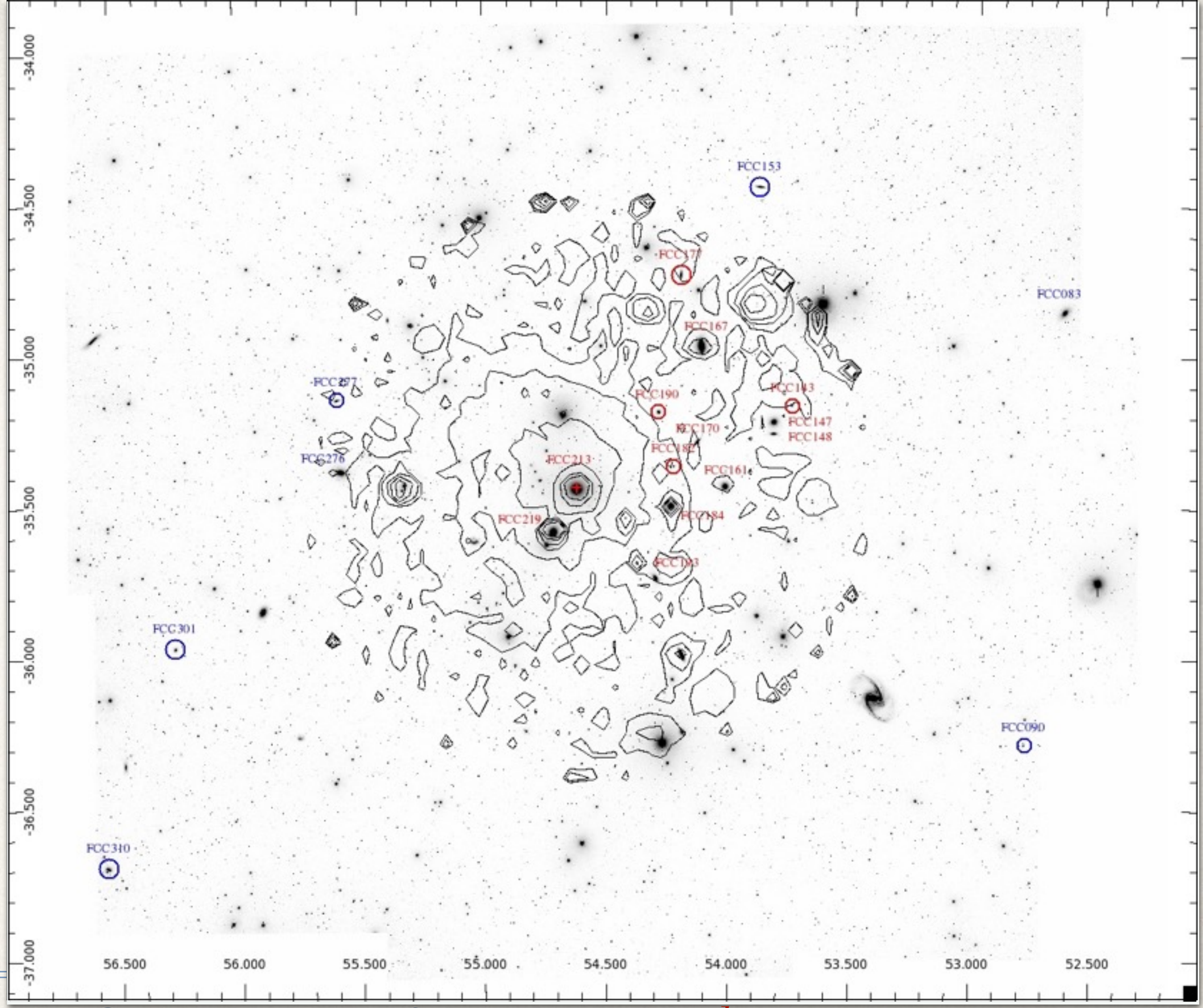


asymmetric stellar halos



The bright ETGs in the R_{vir} of the cluster: *color segregation*

Iodice et al. 2019, A&A, 623, A1



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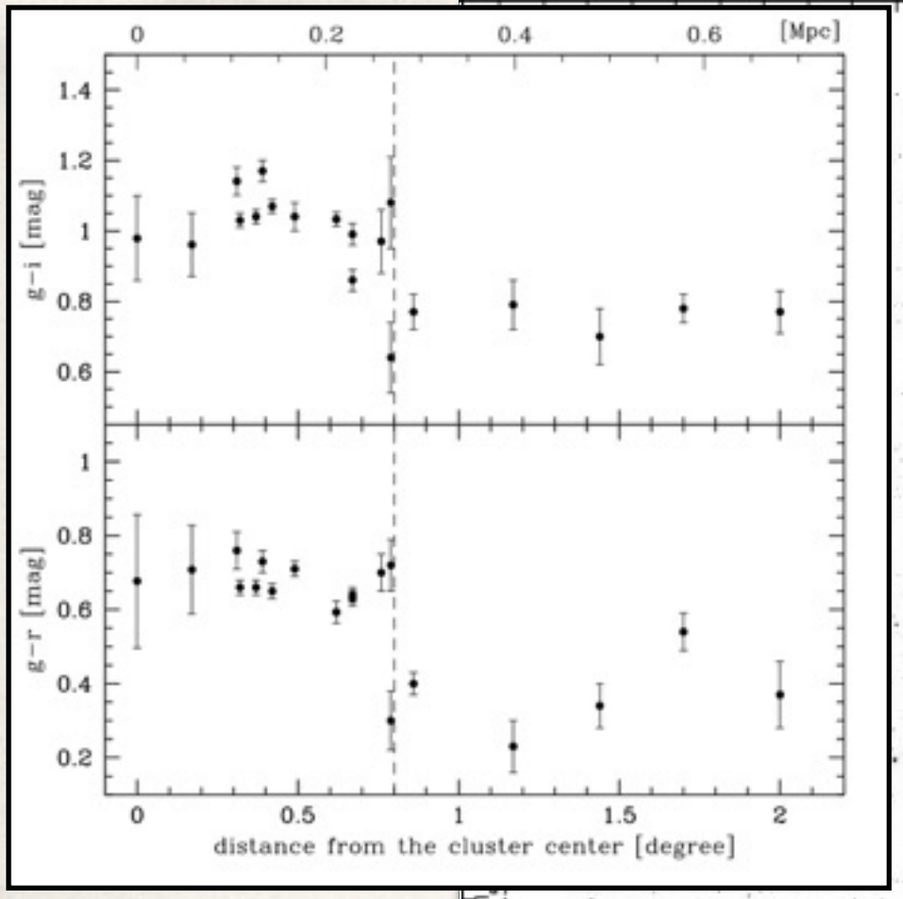

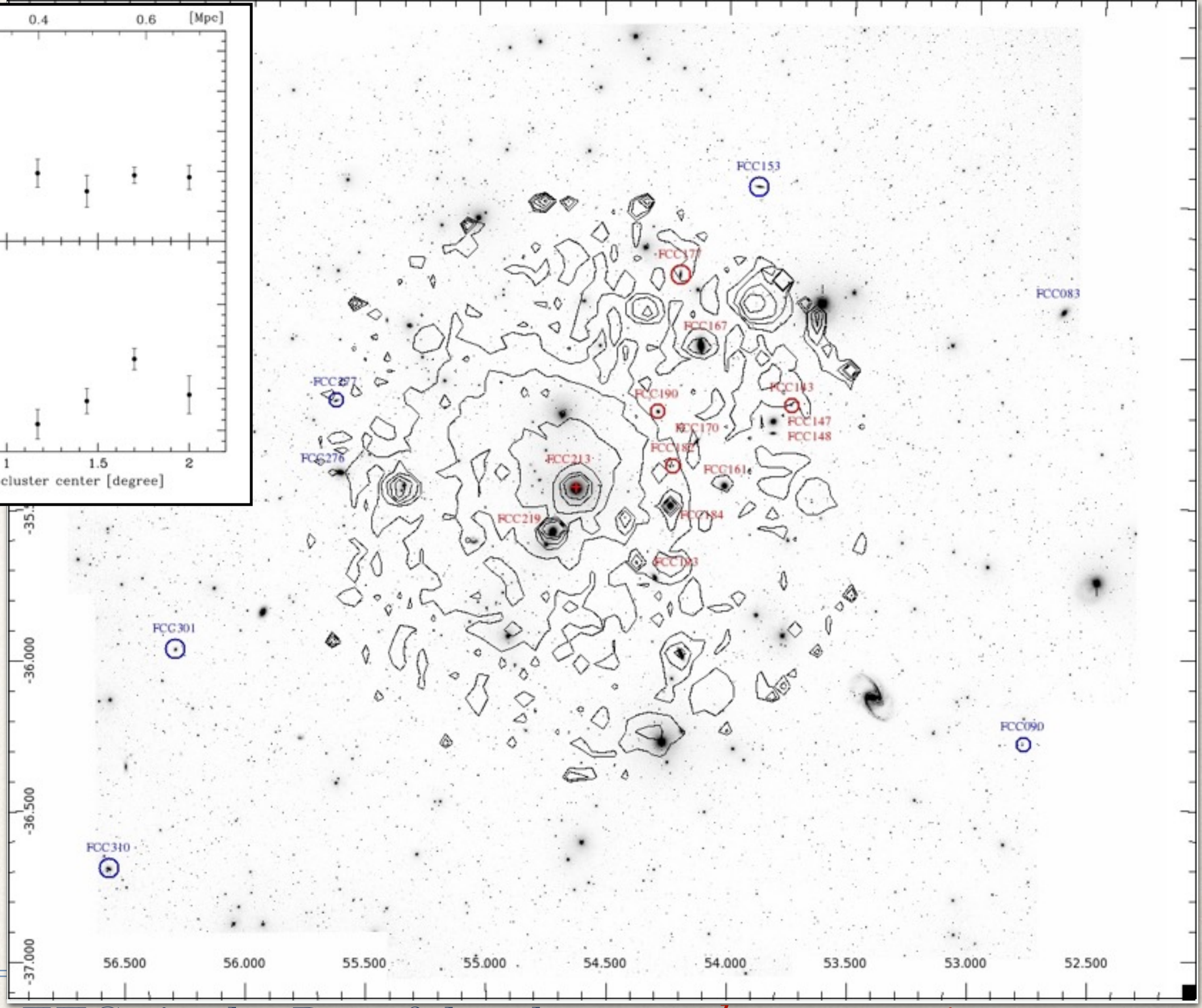

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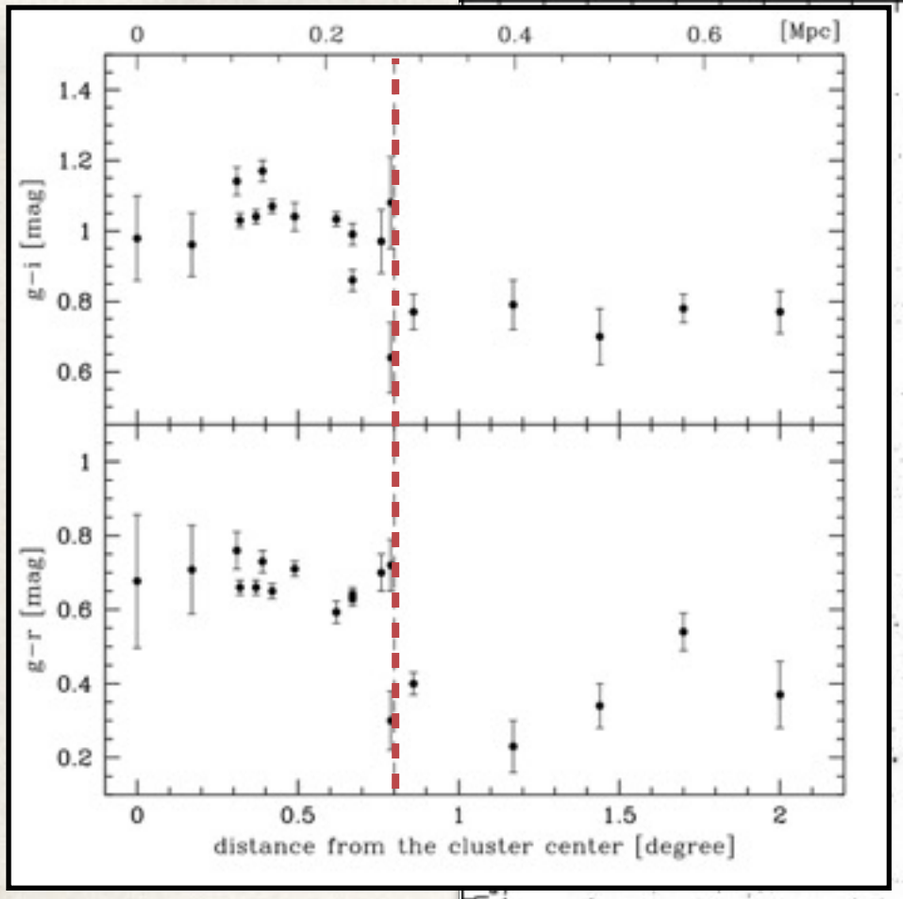

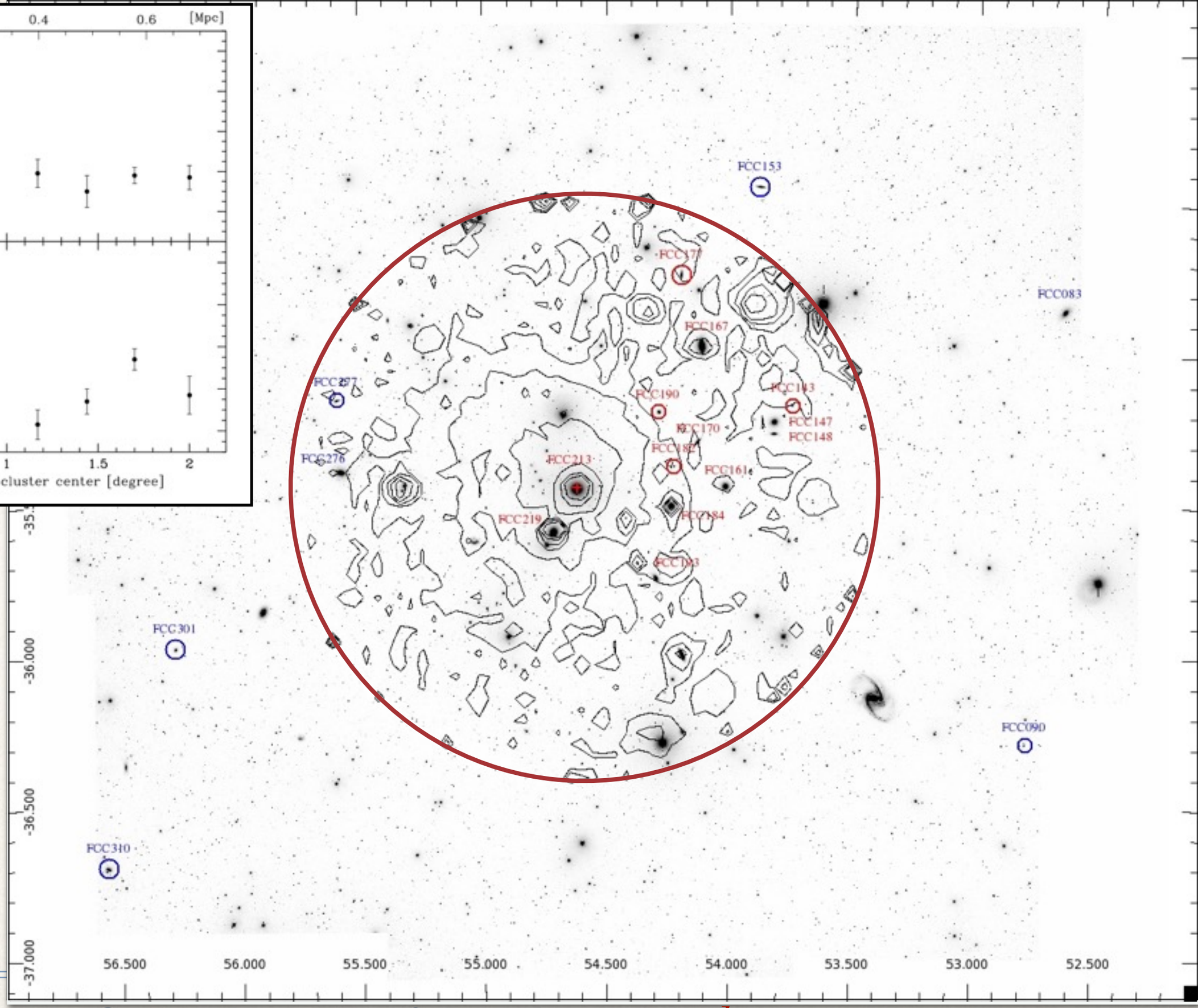

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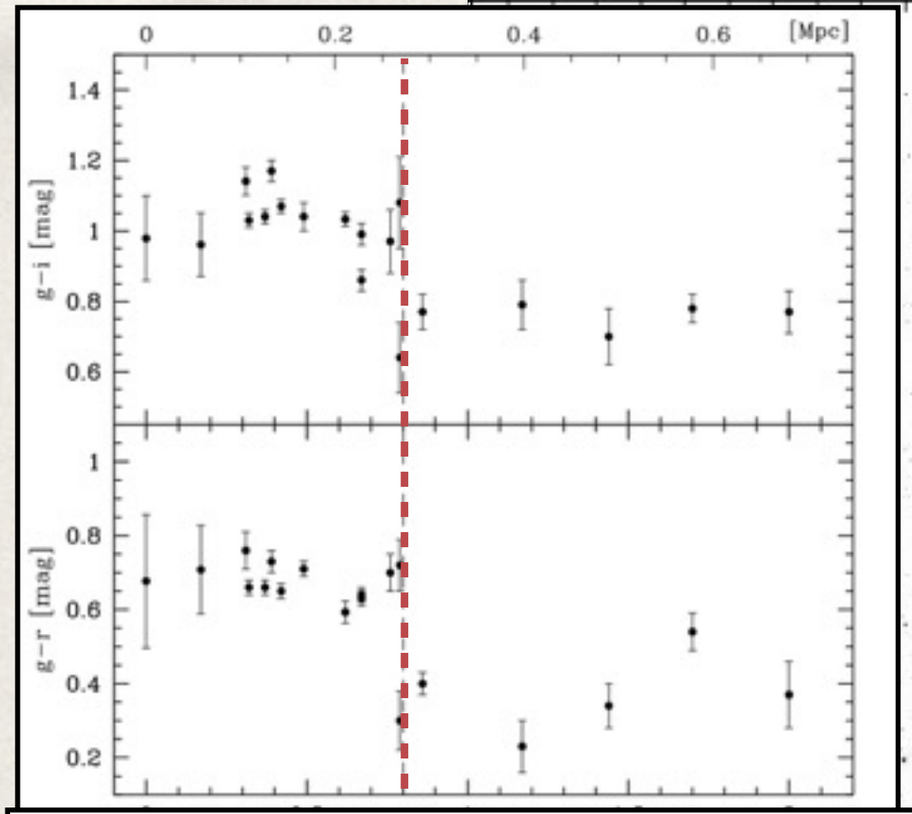
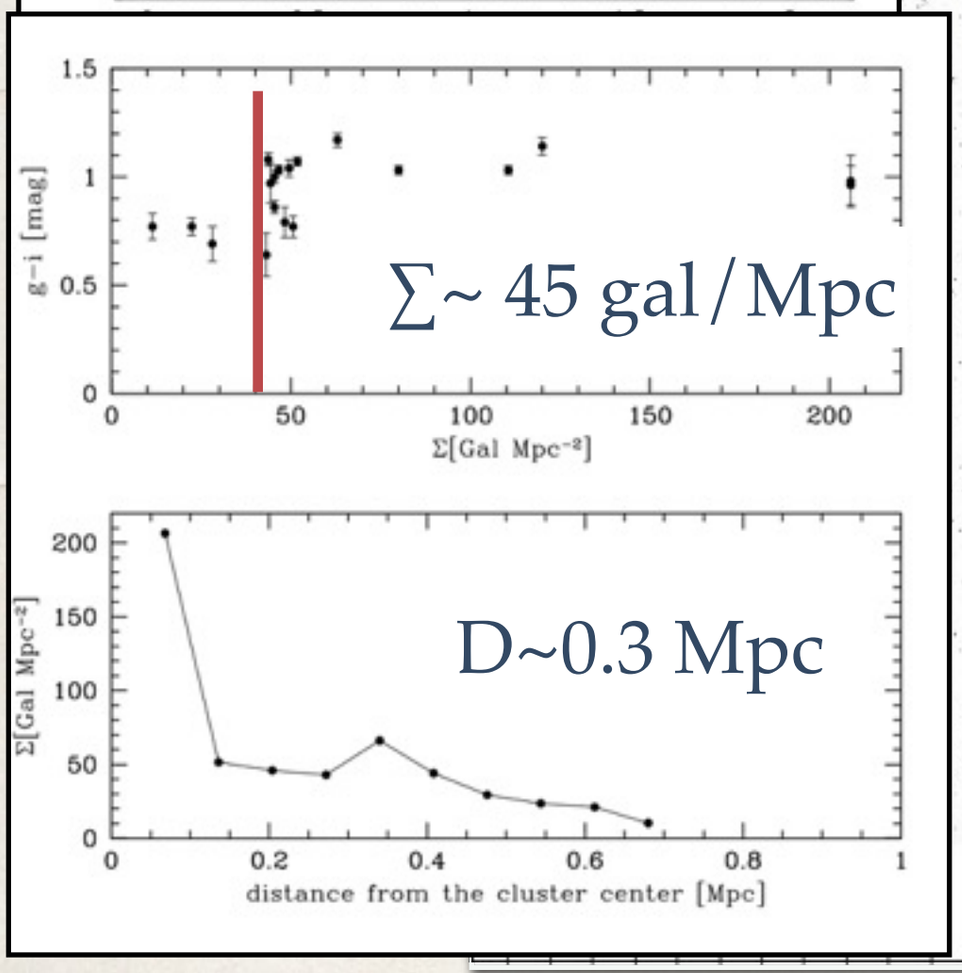
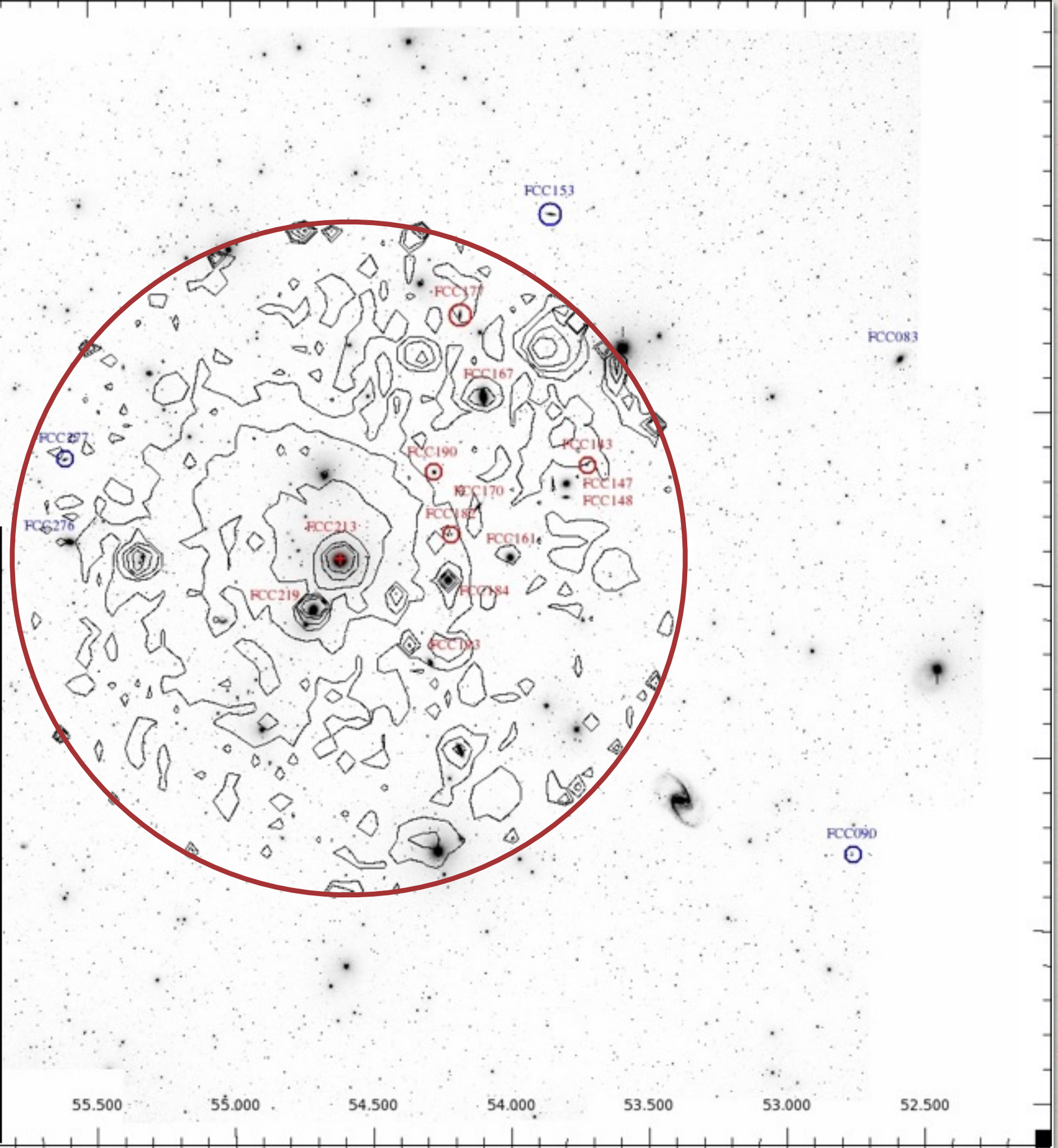


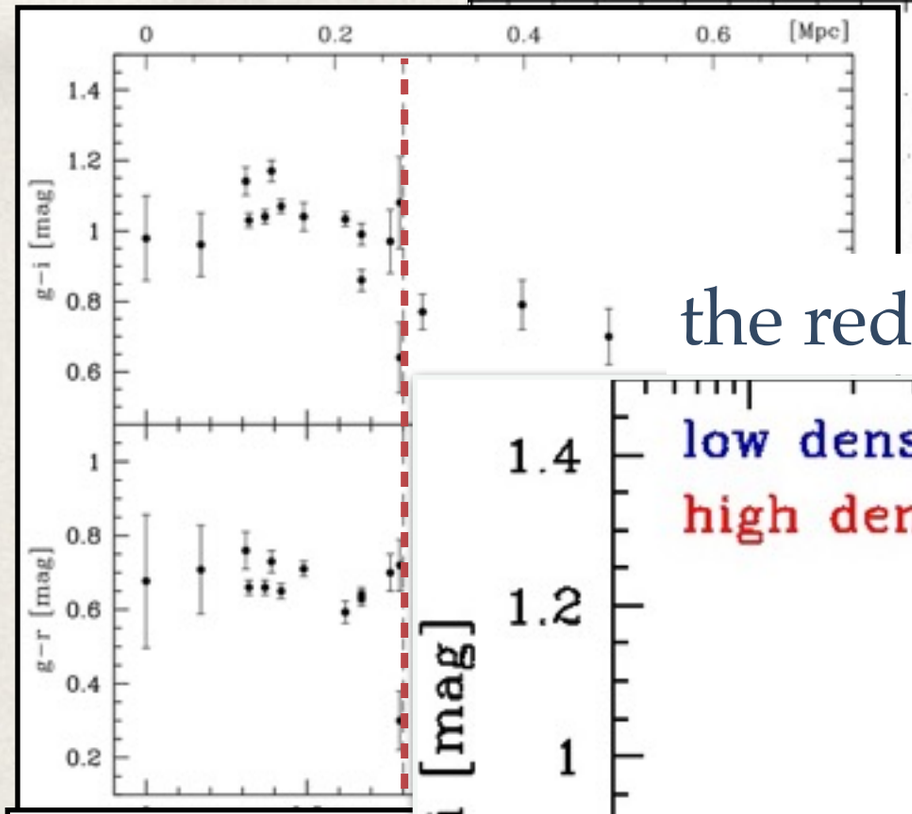


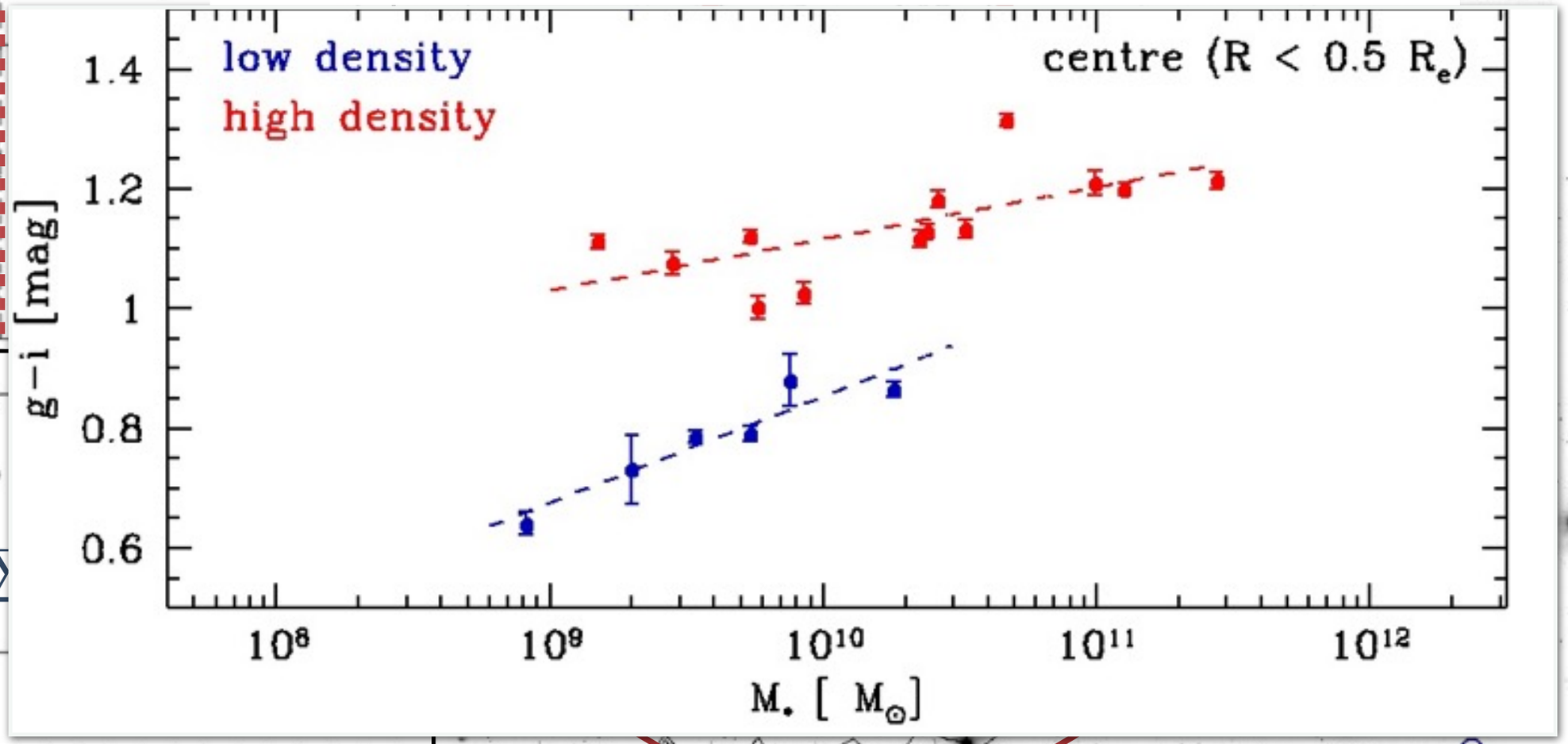


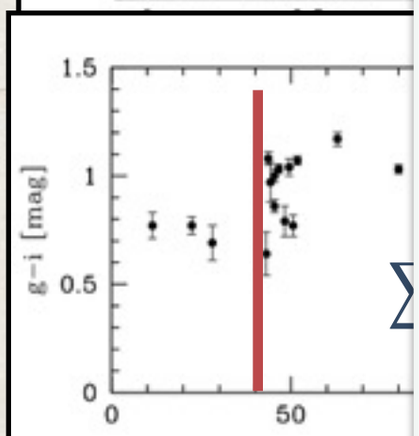
The bright ETGs in the R_{vir} of the cluster: *color segregation*

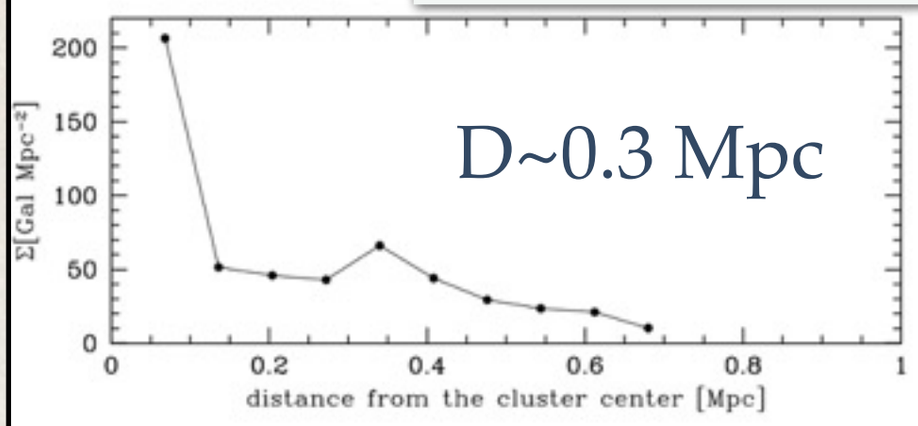
Iodice et al. 2019, A&A, 623, A1

the redder ETGs are in the high-density region







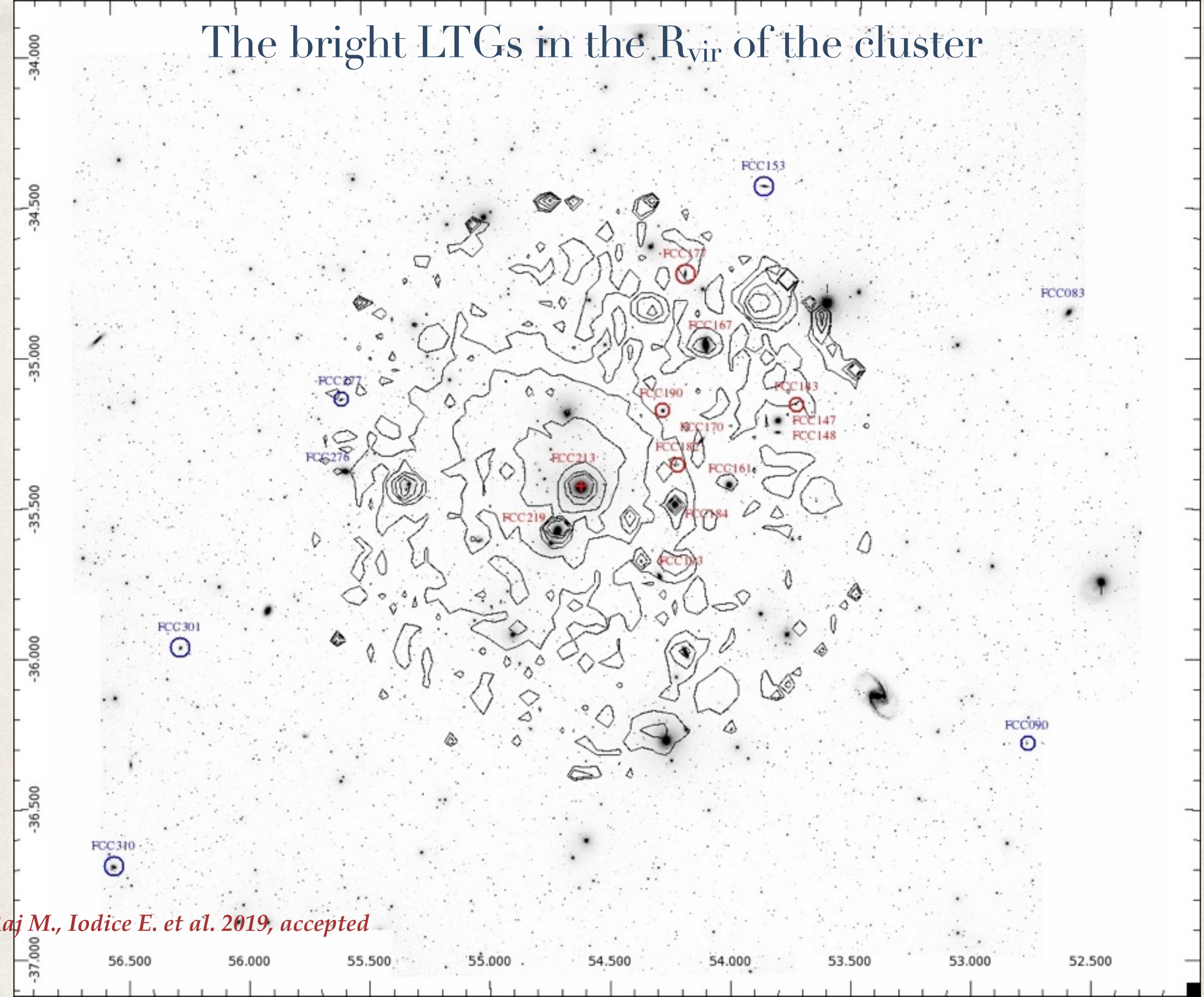


D~0.3 Mpc

The bright ETGs in the R_{vir} of the cluster: *color segregation*

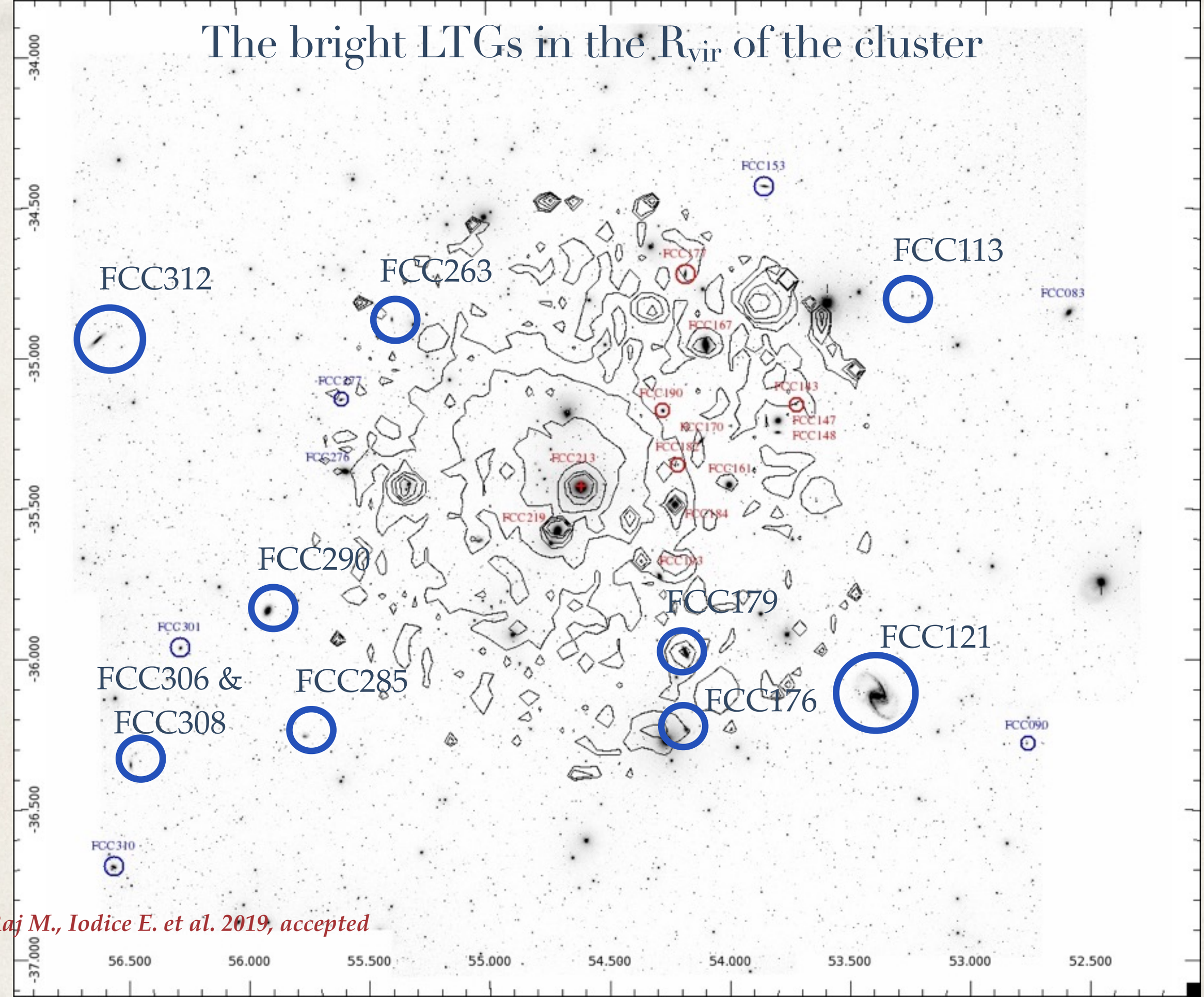
Iodice et al. 2019, A&A, 623, A1

The bright LTGs in the R_{vir} of the cluster



Raj M., Iodice E. et al. 2019, accepted

The bright LTGs in the R_{vir} of the cluster



Raj M., Iodice E. et al. 2019, accepted

The bright LTGs in the B$_{vir}$ of the cluster

FCC113

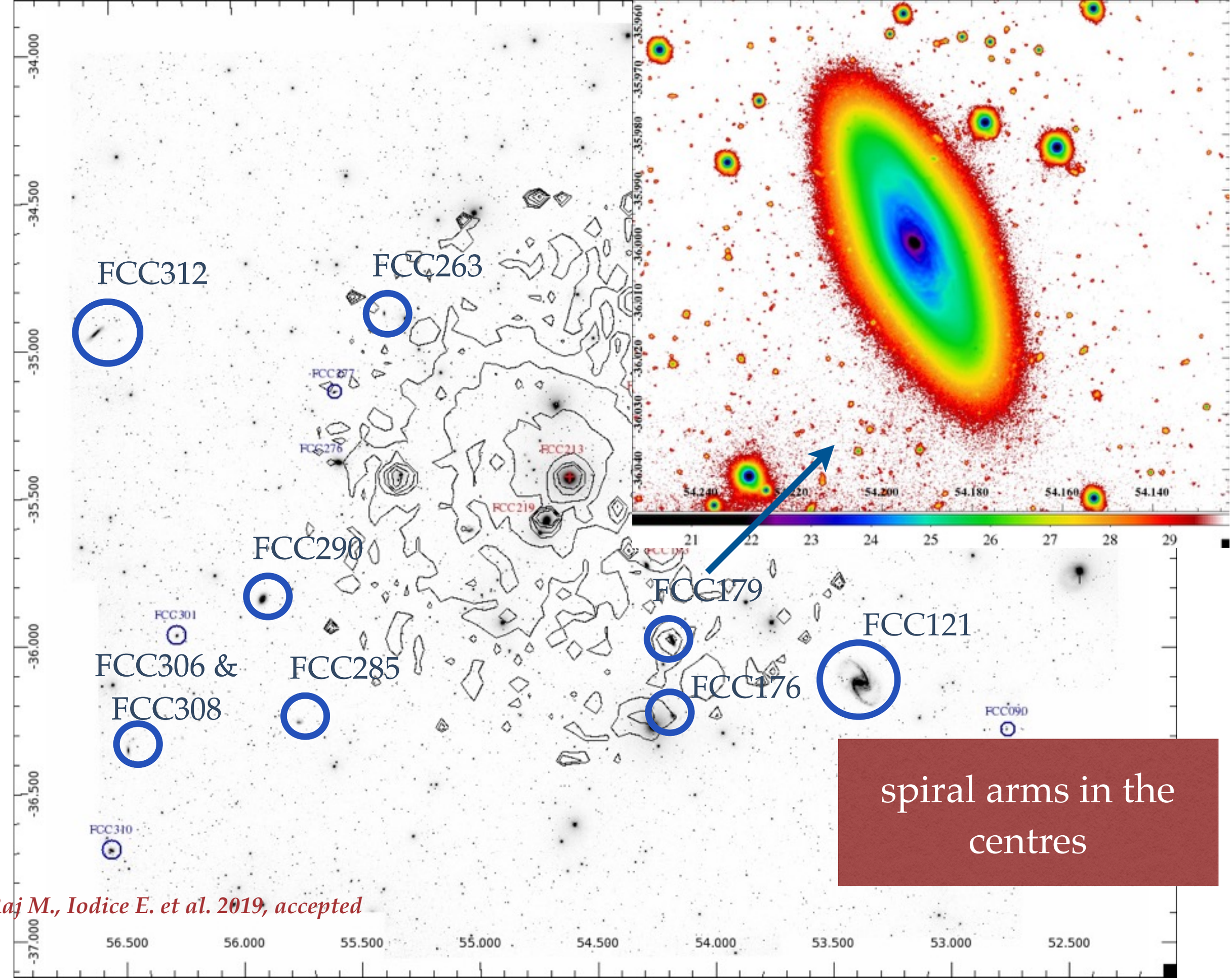
FCC121

FCC306 &
FCC308

FCC285

FCC176

Raj M., Iodice E. et al. 2019, accepted



spiral arms in the centres

Raj M., Iodice E. et al. 2019, accepted

FCC290

FCC179

FCC121

FCC306 &
FCC308

FCC285

FCC176

spiral arms in the centres

Raj M., Iodice E. et al. 2019, accepted

lopsided / jellyfish-like

FCC153

FCC113

FCC083

FCC177

FCC167

FCC190

FCC143

FCC147

FCC148

FCC170

FCC182

FCC213

FCC184

FCC179

FCC121

FCC176

FCC090

FCC310

FCC306 &
FCC308

FCC285

↑ the R_{vir} of the cluster

Raj M., Iodice E. et al. 2019, accepted

lopsided / jellyfish-like

Cluster centre

FCC153

FCC177

FCC167

FCC083

FCC113

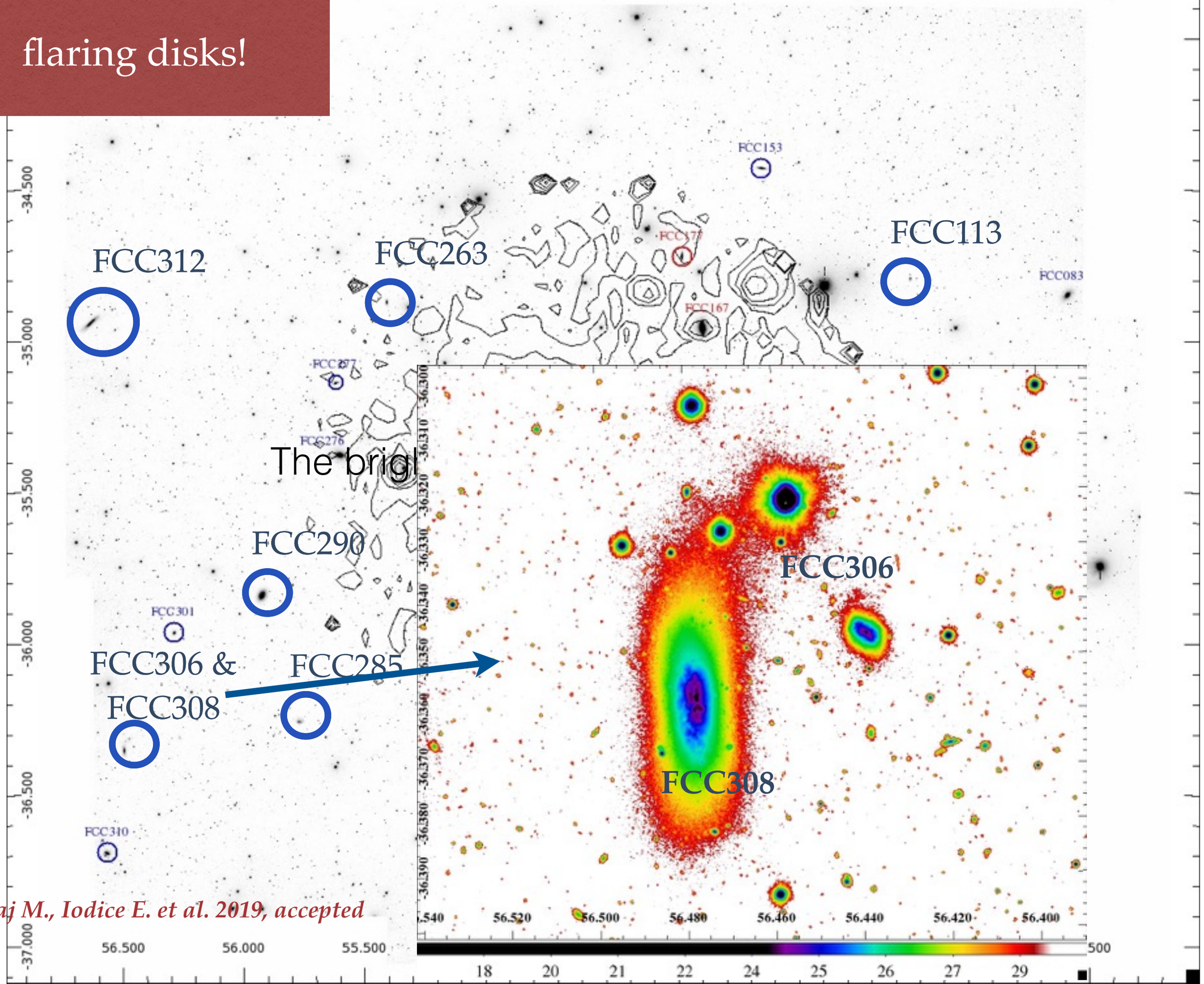
FCC306 &
FCC308

FCC285

FCC310

Raj M., Iodice E. et al. 2019, accepted

flaring disks!



Raj M., Iodice E. et al. 2019, accepted

flaring disks!

FCC312

FCC290

FCC301

FCC306 &
FCC308

FCC285

FCC310

FCC113

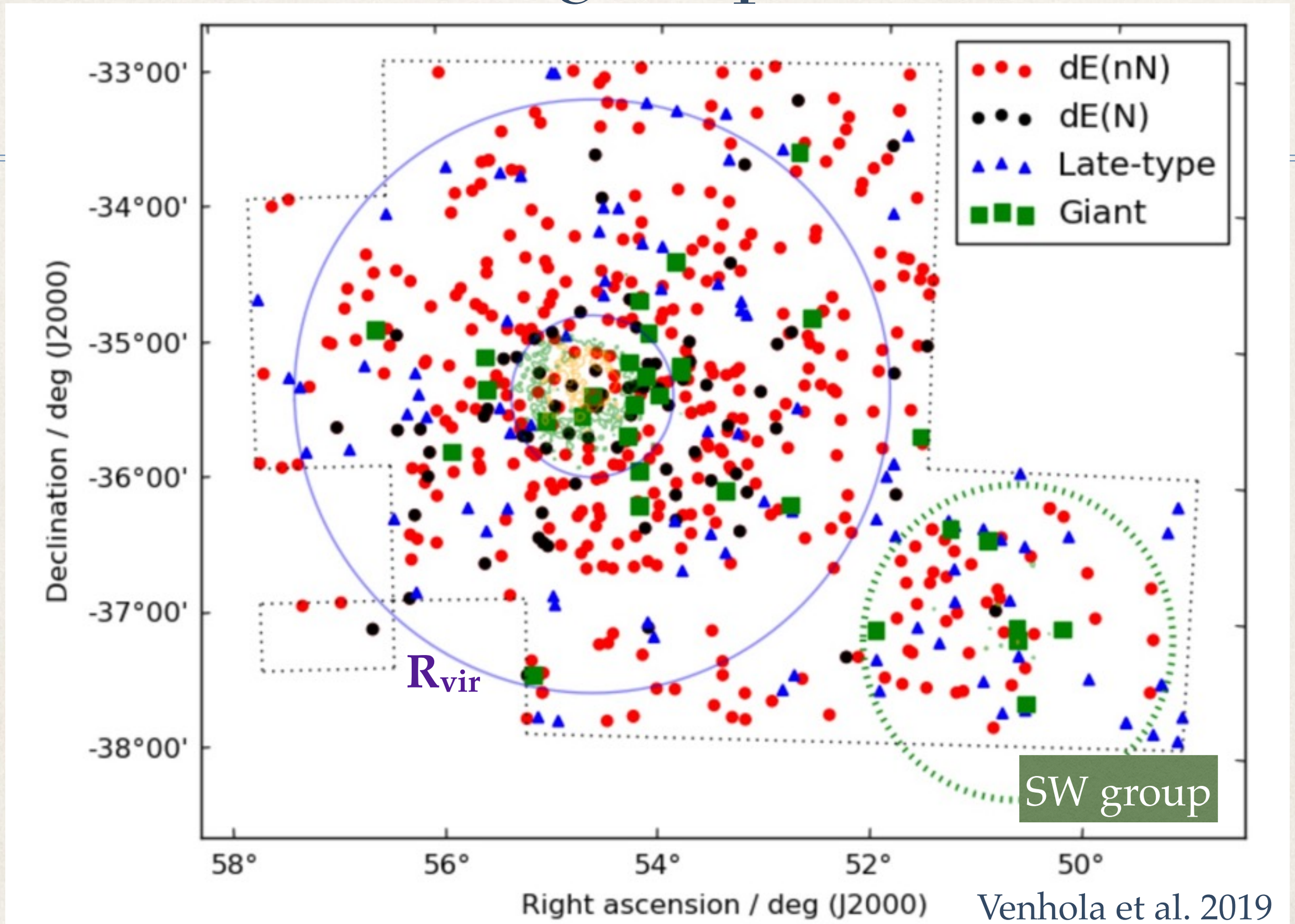
FCC083

FCC306

FCC308

Raj M., Iodice E. et al. 2019, accepted

FDS: the SW group



Venhola et al. 2019

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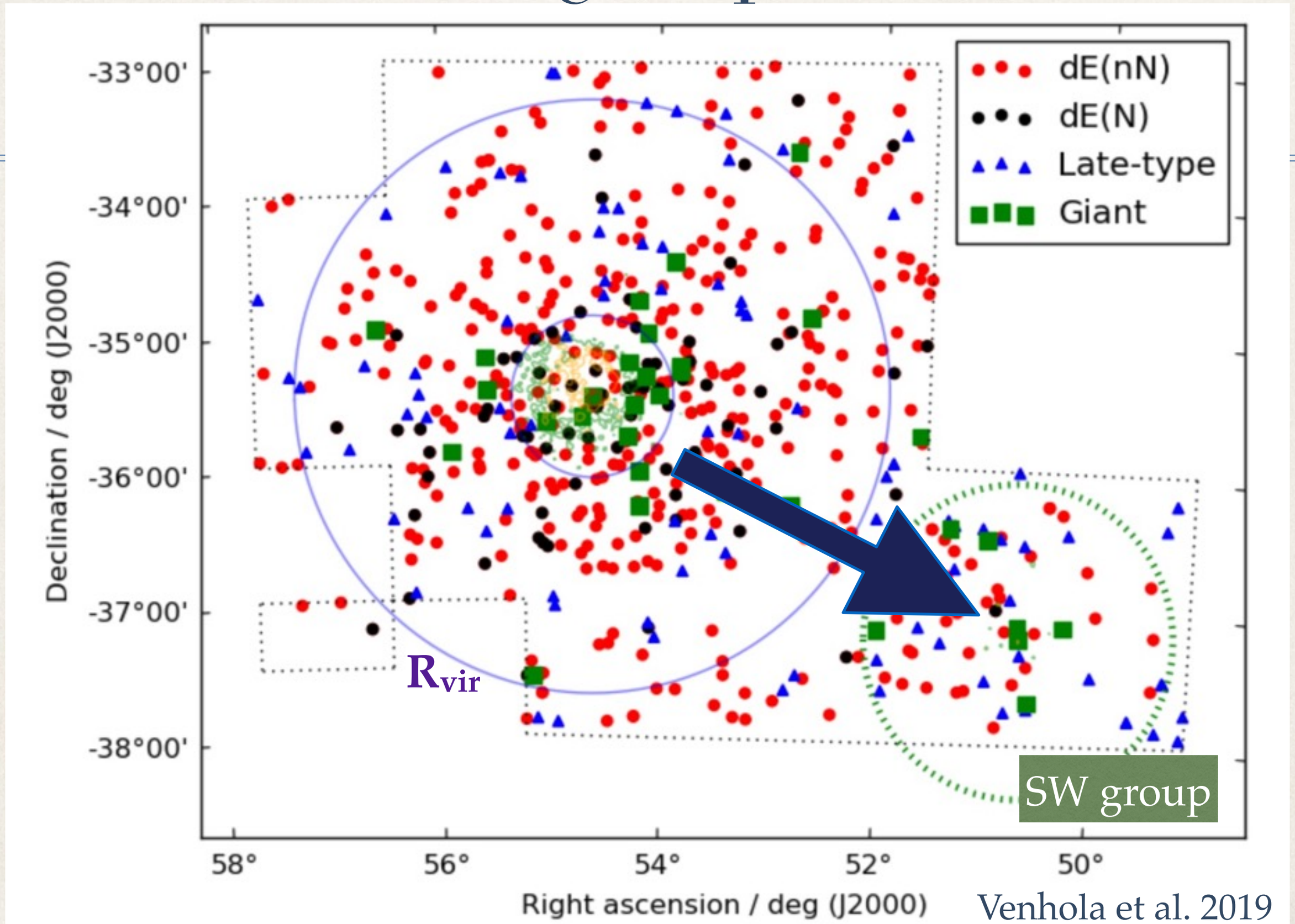
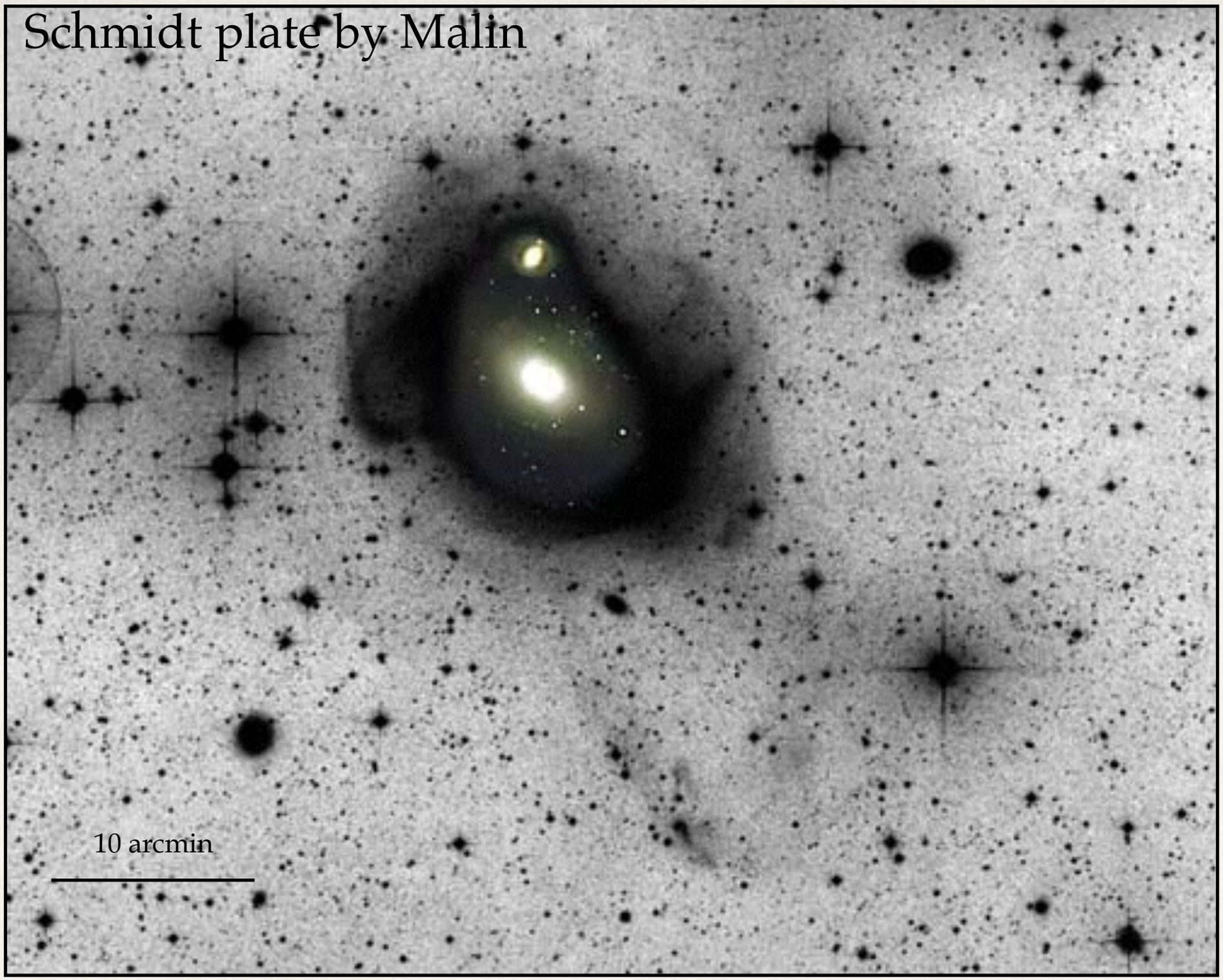
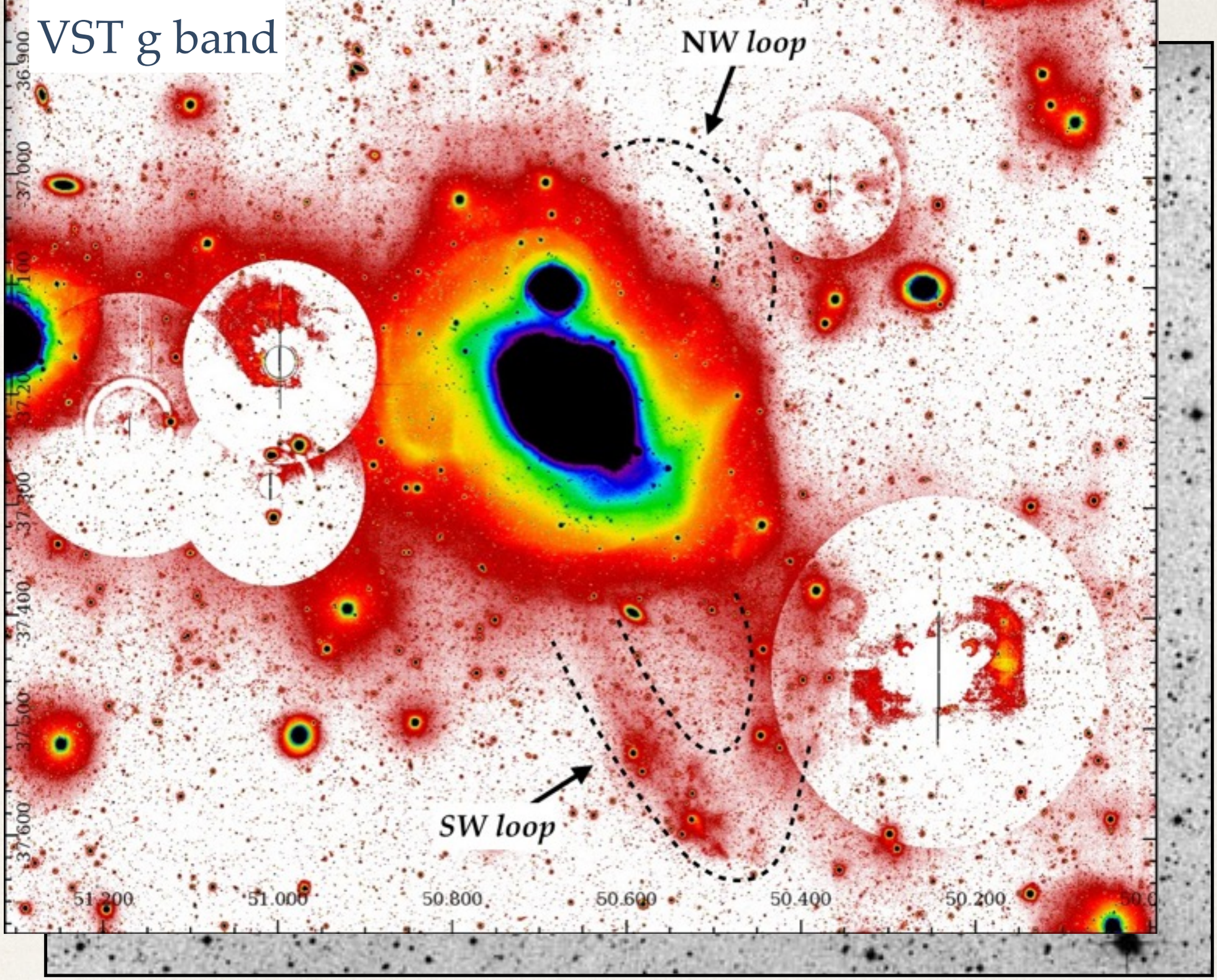


Venhola et al. 2019



Fornax A: a two-phase assembly caught in act

Iodice et al. 2017, ApJ, 839, 21



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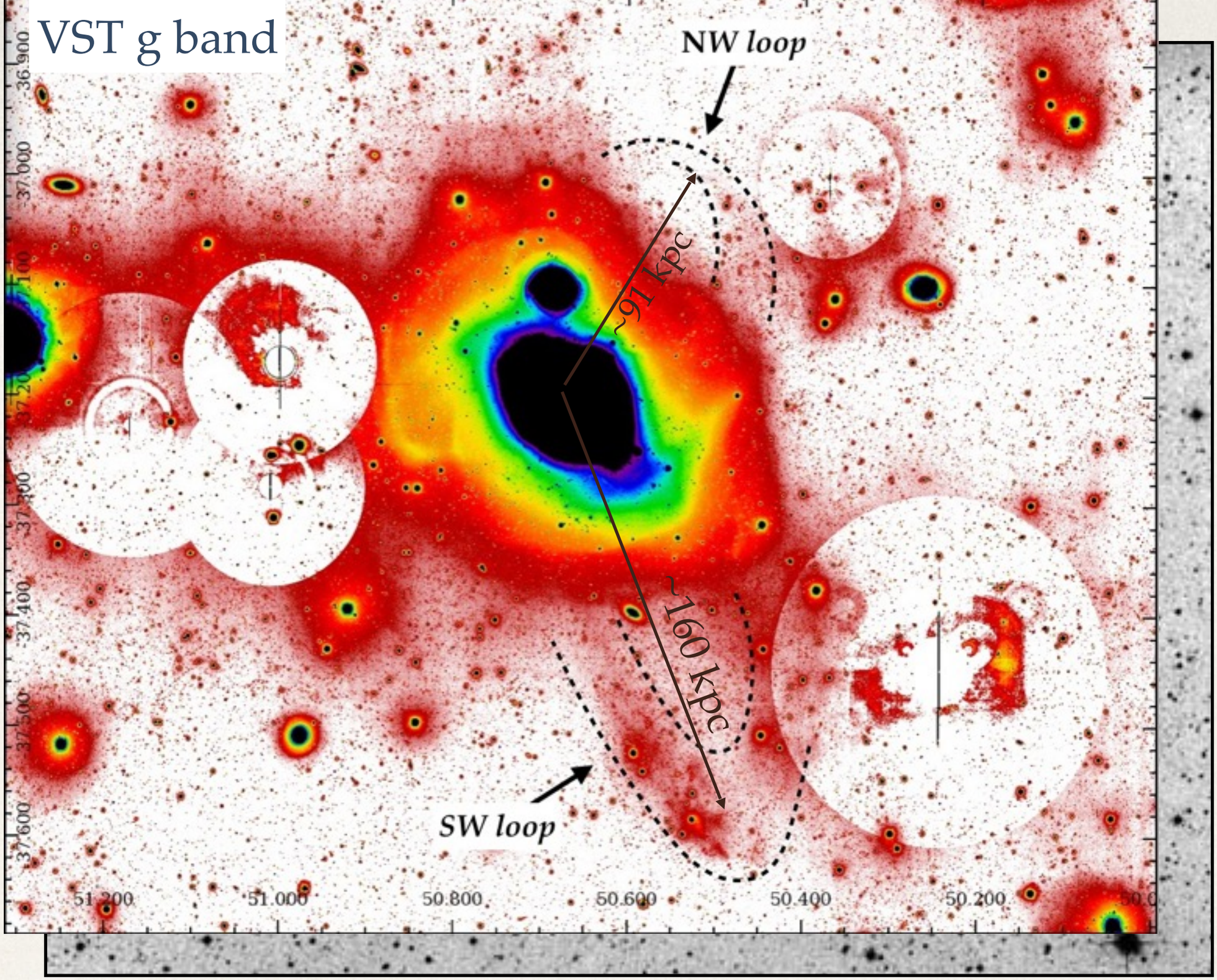
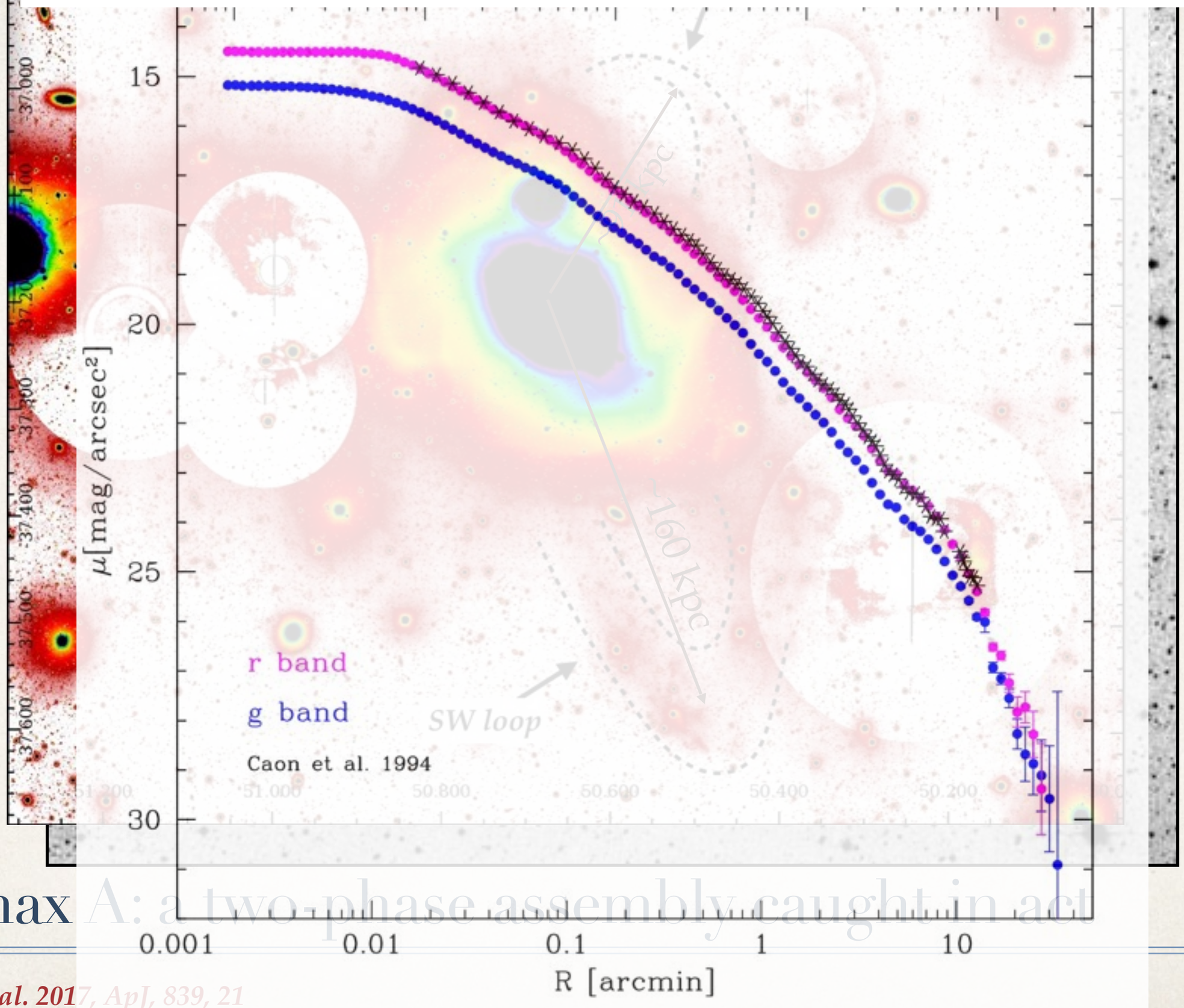


Fornax A: a two-phase assembly caught in act

Iodice et al. 2017, ApJ, 839, 21

surface photometry out to 33 arcmin (~200 kpc ~15R_e)



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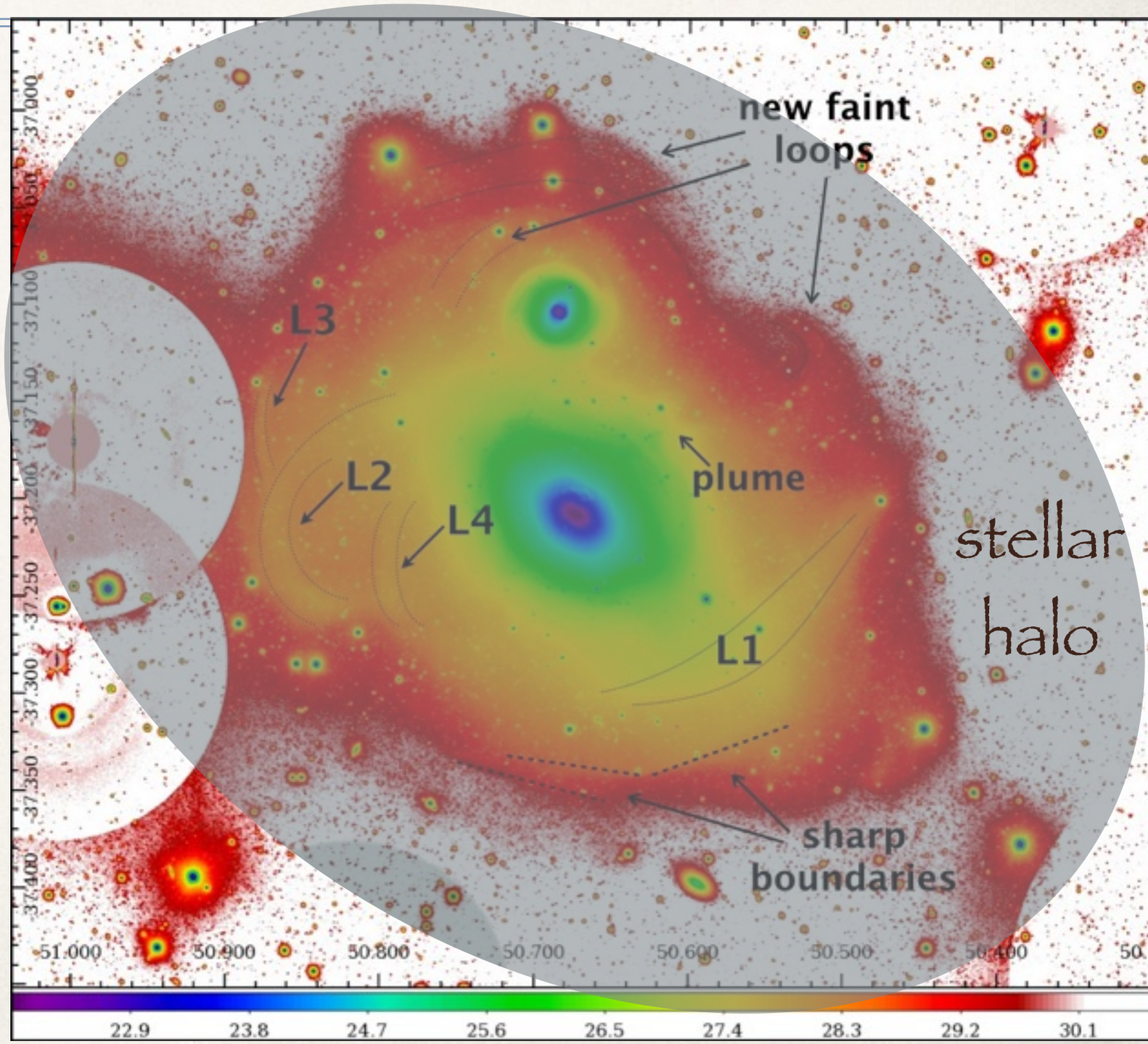
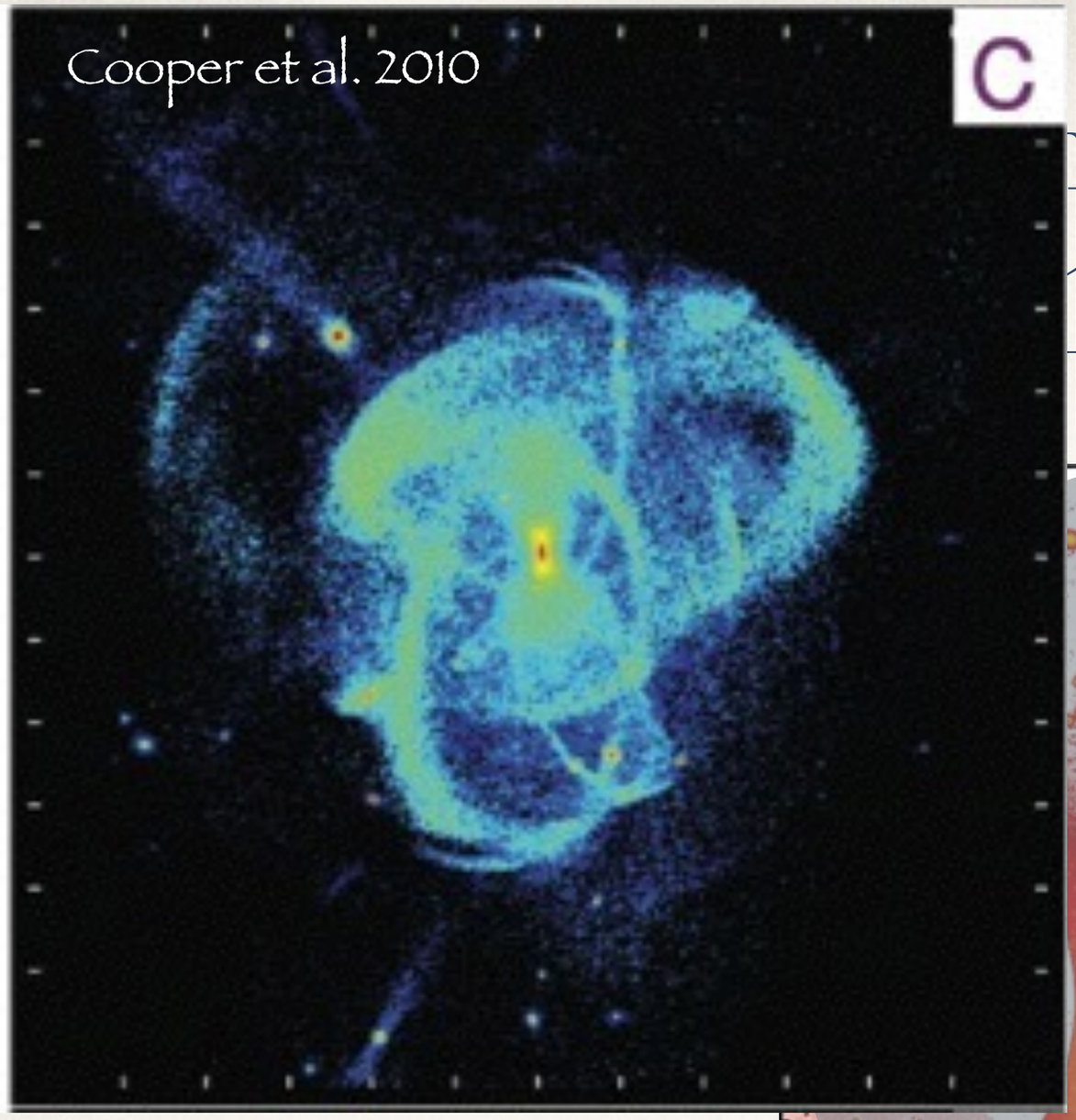
Iodice et al. 2017, ApJ, 839, 21

the build up of the stellar halo in NGC1316

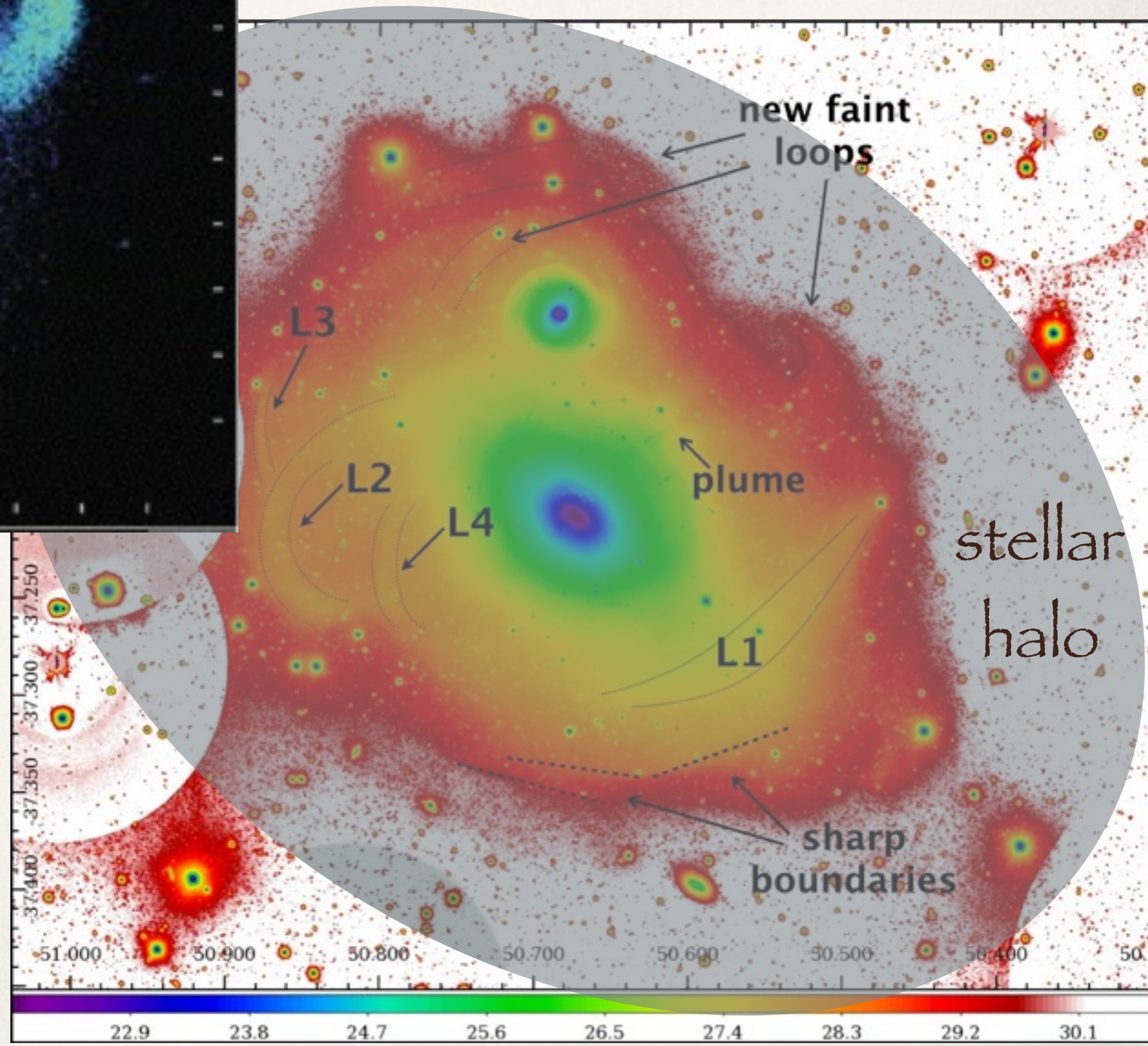


Cooper et al. 2010



stellar halo in NGC1316 formed by gradual accretion of several progenitors:

similar morphology + total extension



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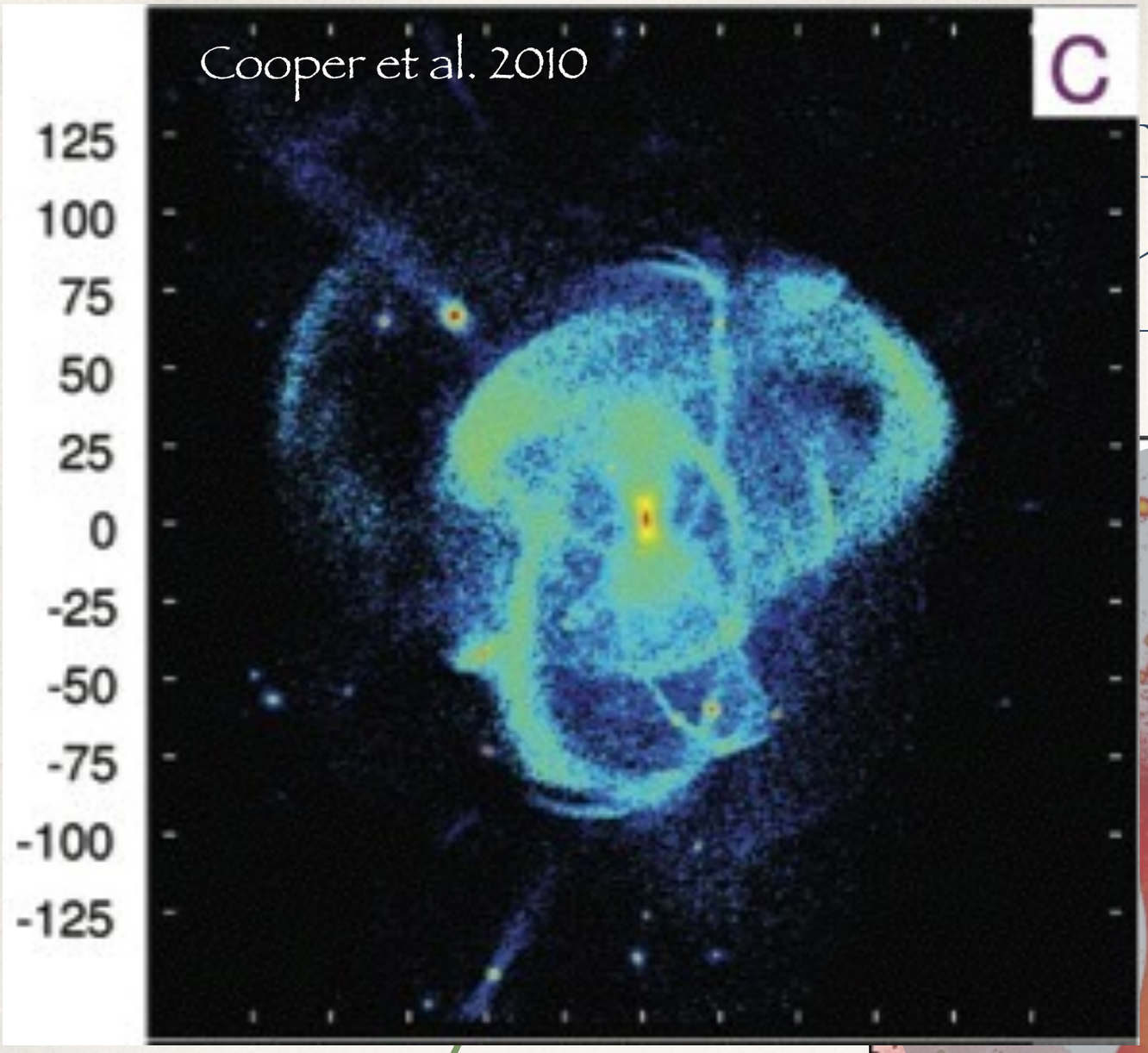
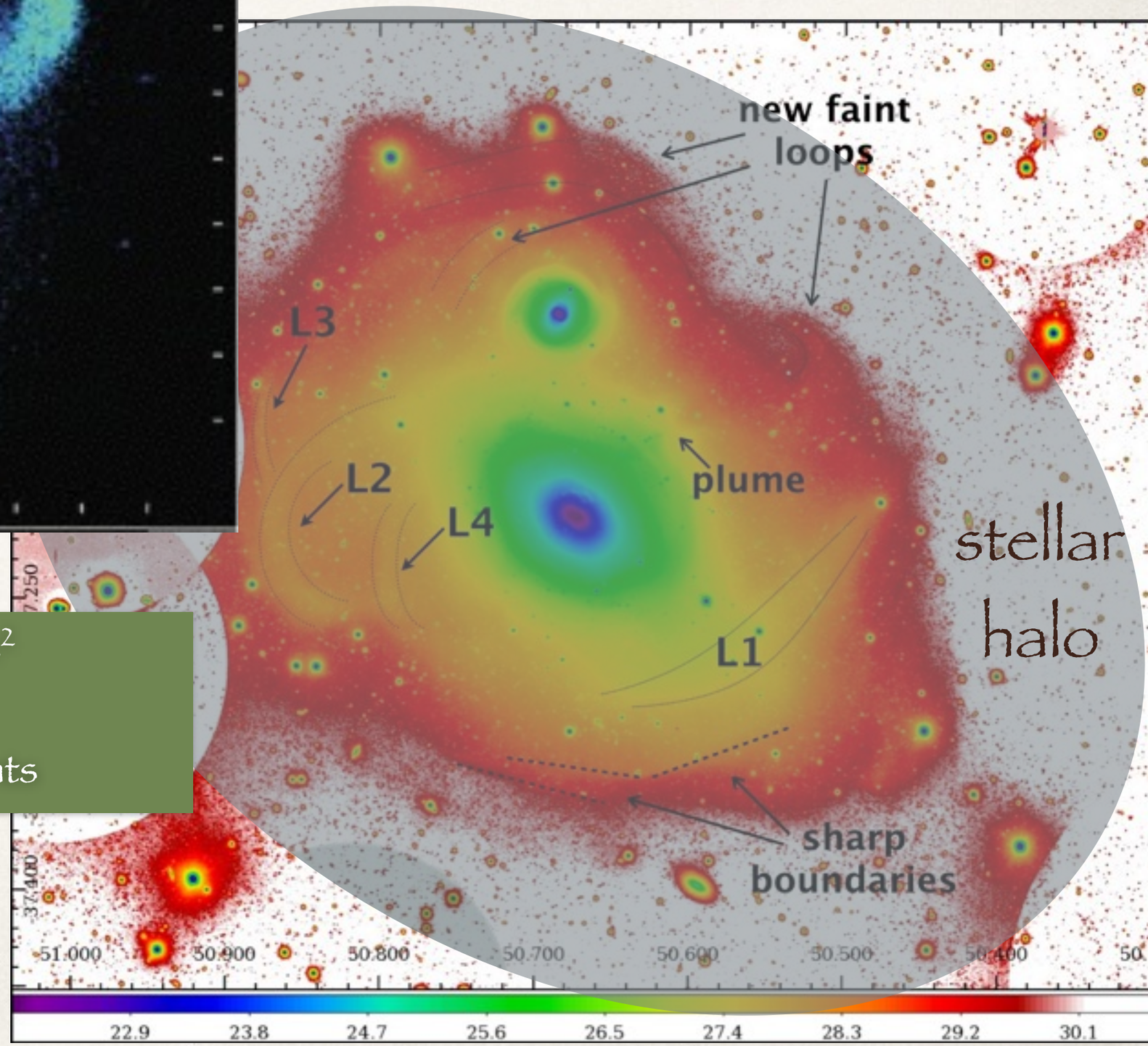
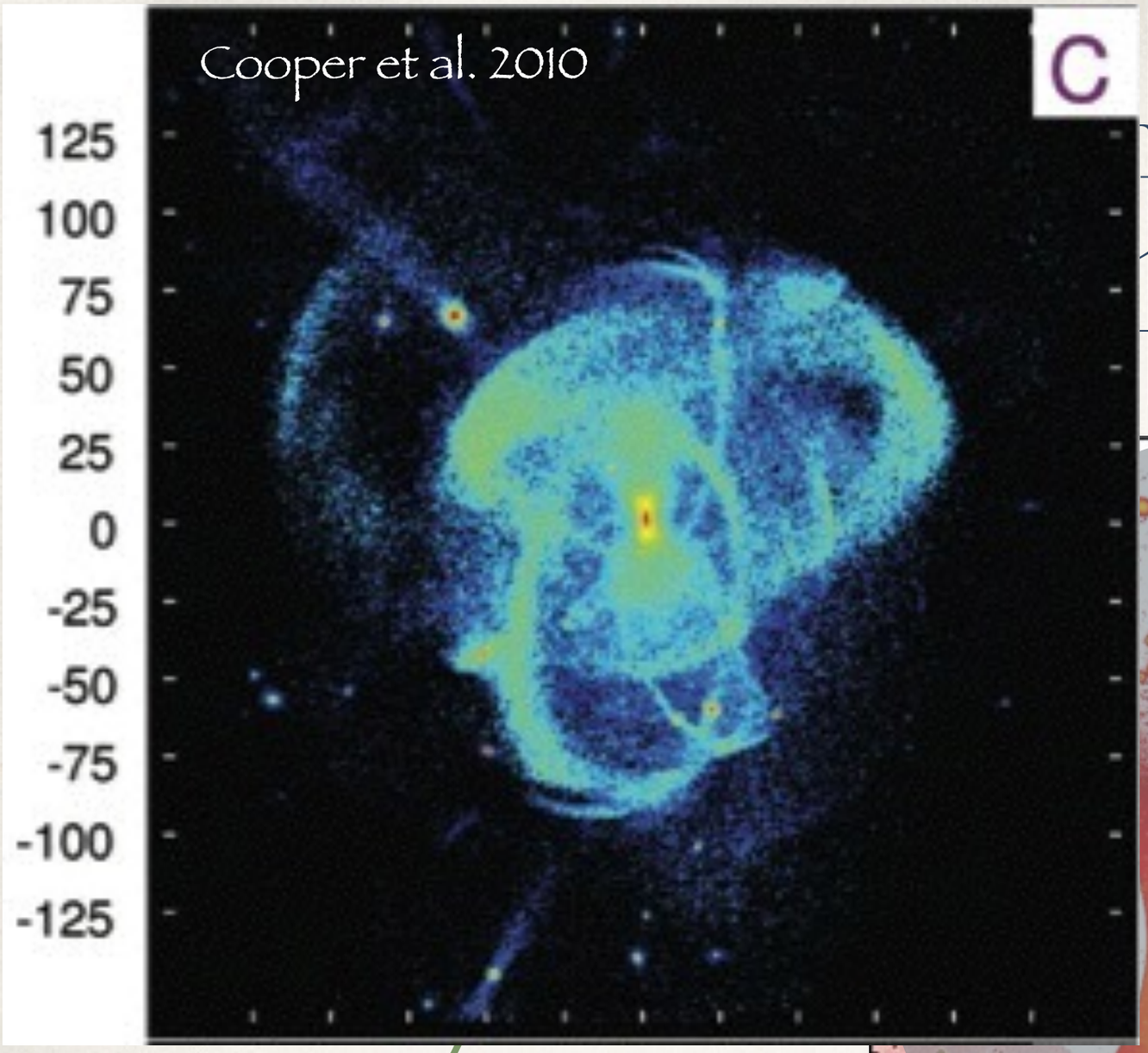


- SB (r band) ≈ 26.6 - 30.6 mag/arcsec^2
- exponential profile
- luminous substructures ≈ recent events





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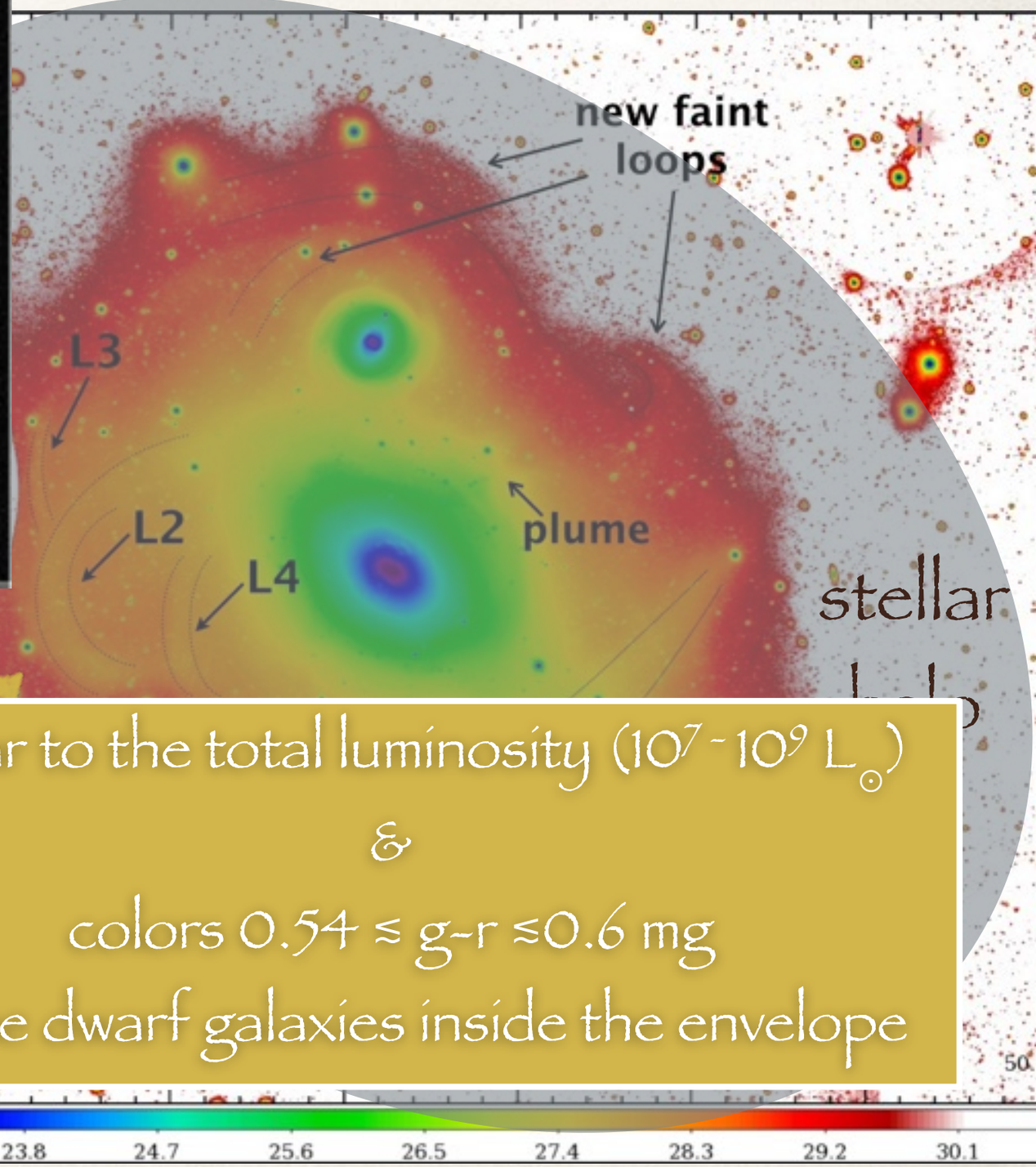

- SB (r band) = 26.6 - 30.6 mag/arcsec^2
- exponential profile
- luminous substructures = recent events

$L_{(L2+L3)} = 7\,10^9\ L_\odot$

g-r =0.54 mag

similar to the total luminosity (10^7 - 10^9 $L_\odot$)

&

colors 0.54 ≤ g-r ≤0.6 mg

of the dwarf galaxies inside the envelope

Concluding summary on Fornax cluster from FDS

- observations suggest that the Fornax cluster is not completely relaxed
- the bulk of the gravitational interactions are in the W-NW core region <=> most of the ETGs + ICL + LSB structures are found
- the W-NW sub-clump of galaxies merging in the cluster core
- Differently from NGC1399, the faint envelope in NGC1316 still hosts the remnants of the accreted satellite galaxies
- strong indication of a different galaxy evolution, star formation history and mass assembly as function of the cluster-centric radius

what next on Fornax?

Fornax3D: A magnitude-limited survey of galaxies within the virial radius of the Fornax Cluster with MUSE

http://www.na.astro.it/Fornax3D/Fornax3D/Welcome.html

Team

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Fornax3D: A magnitude-limited survey of galaxies within the virial radius of the Fornax Cluster with MUSE

http://www.na.astro.it/Fornax3D/Fornax3D/Welcome.html

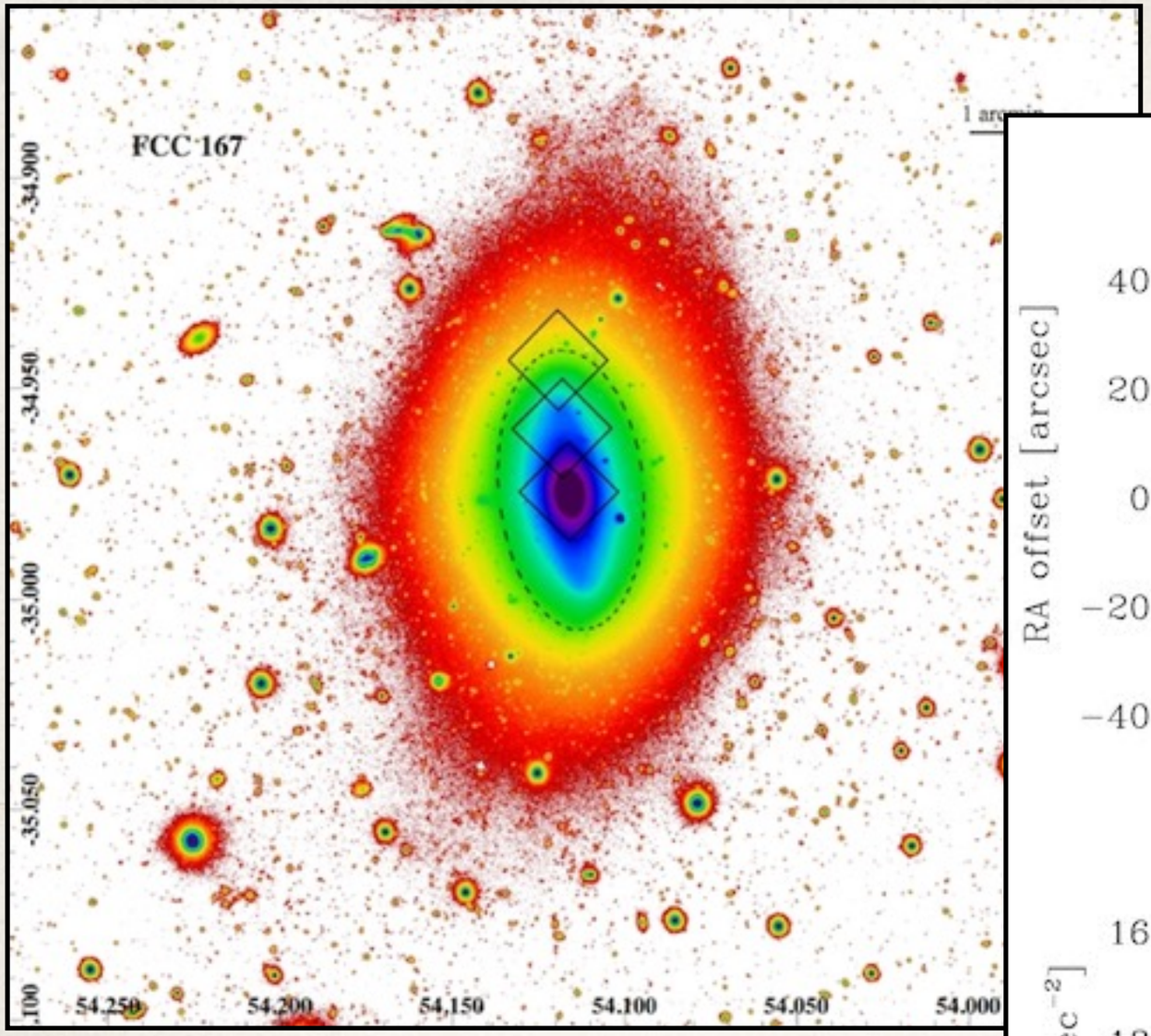
Sarzi, Iodice et al. 2018, A&A, 616, 121

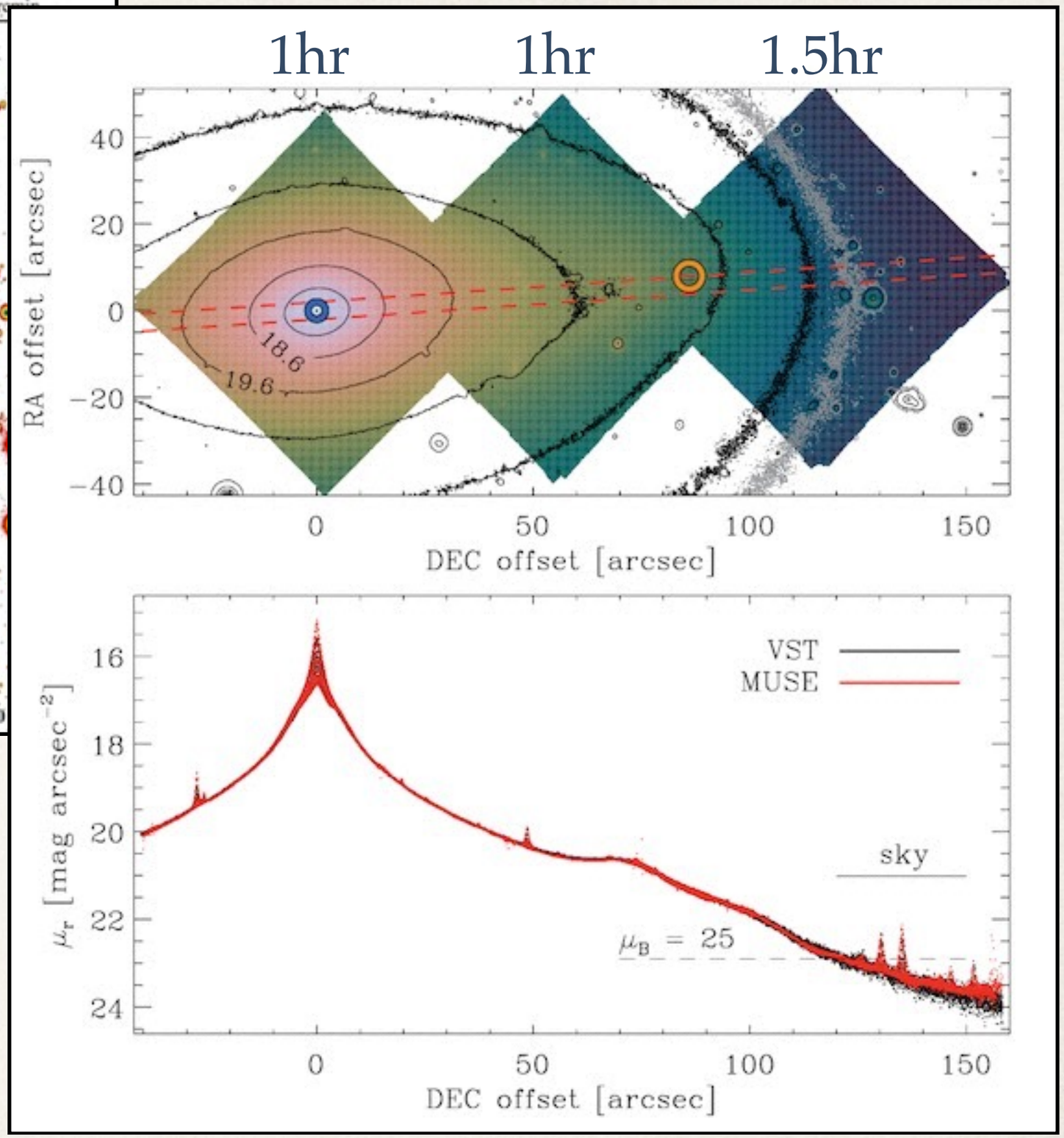
— Survey —

* 2D map of 32 galaxies in the core of the Fornax Cluster
* brighter than M_B=-16
* within the R_{vir} (0.7 Mpc)
* ETGs (23) & LTGs (9)

— science goals —

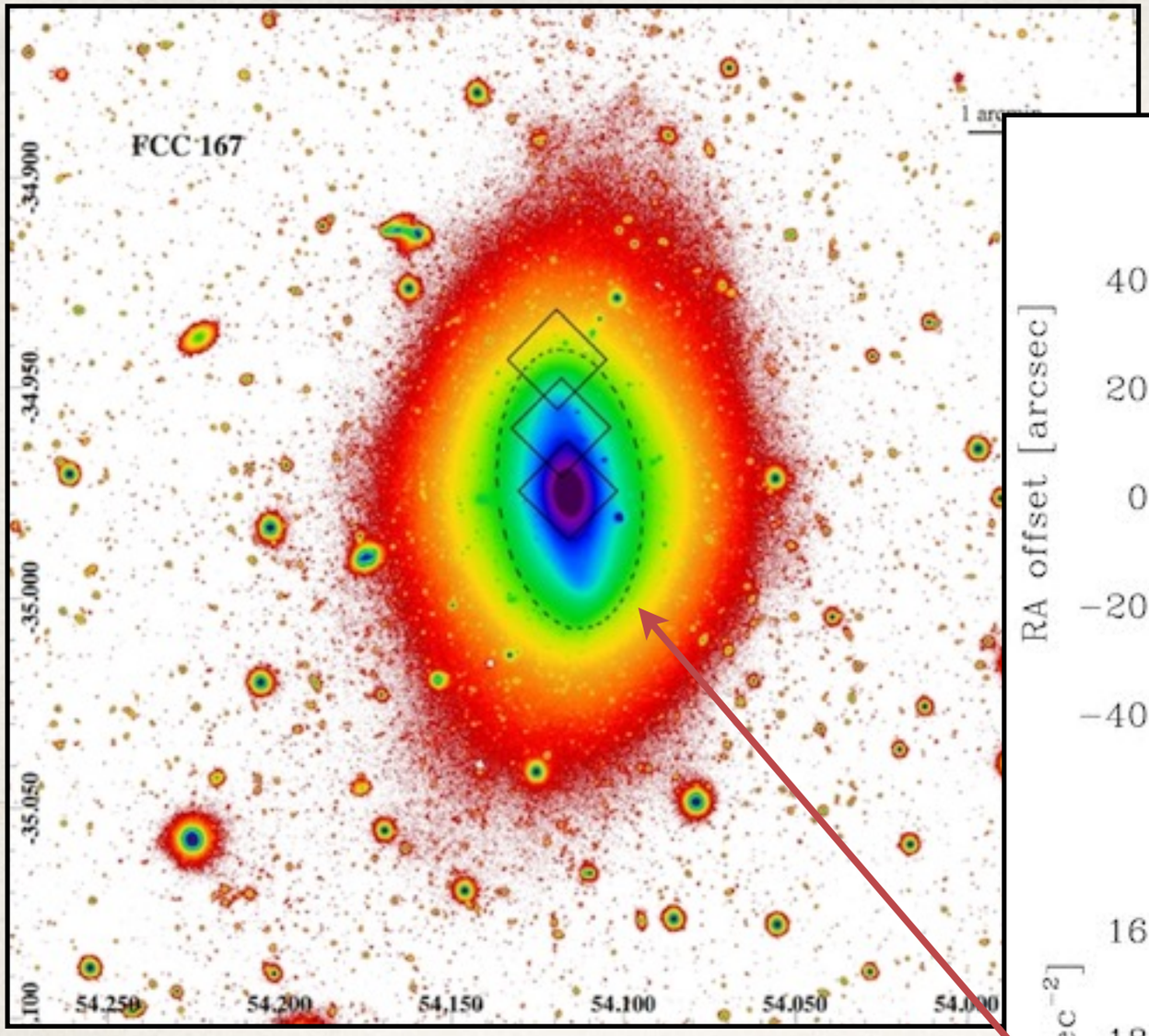
* structural stellar components (bulges, disks, bars, kinematically decoupled structures) via spectral and dynamical modelling decomposition
* IMF and stellar population in halos (~ outside $2R_e$)
* Stellar population: origin of the chemically distinct structures (Mg, Fe, Na disks) and galaxy structural components
* Census of PNe & GCs
* Study and evolution of nuclear stellar disks/clusters

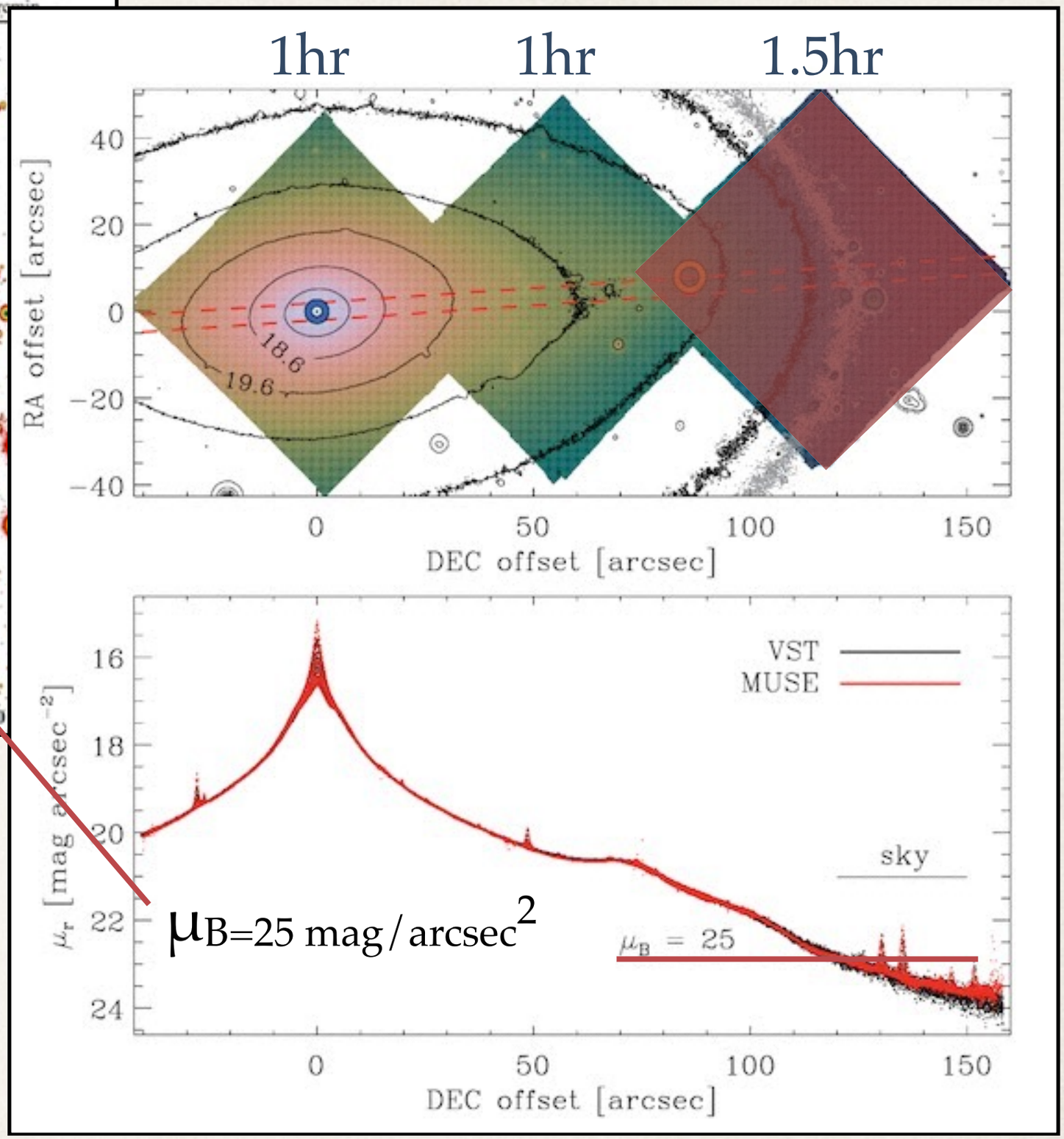




Fornax3D: survey design

Sarzi, Iodice et al. 2018, A&A 616, 121





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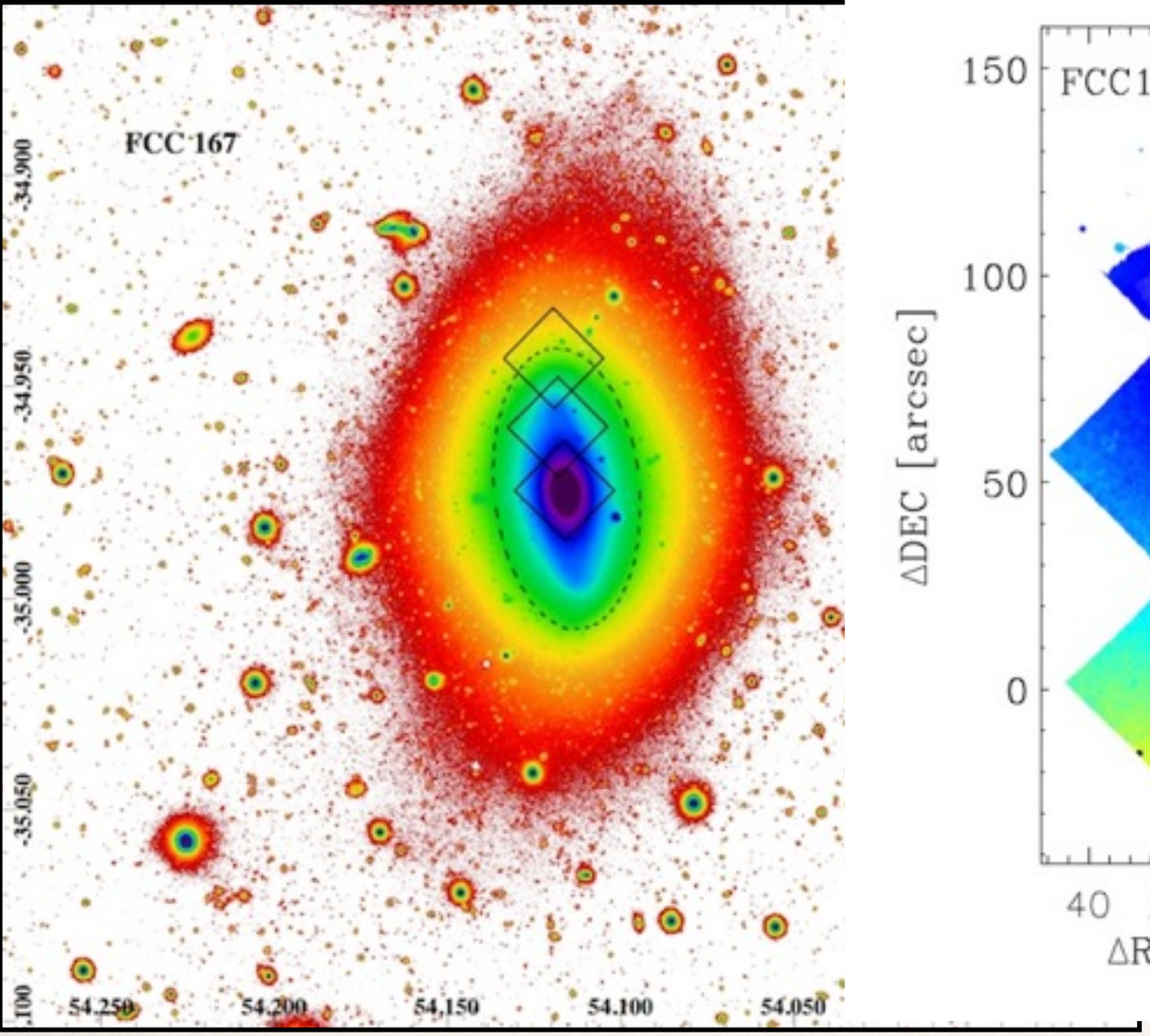
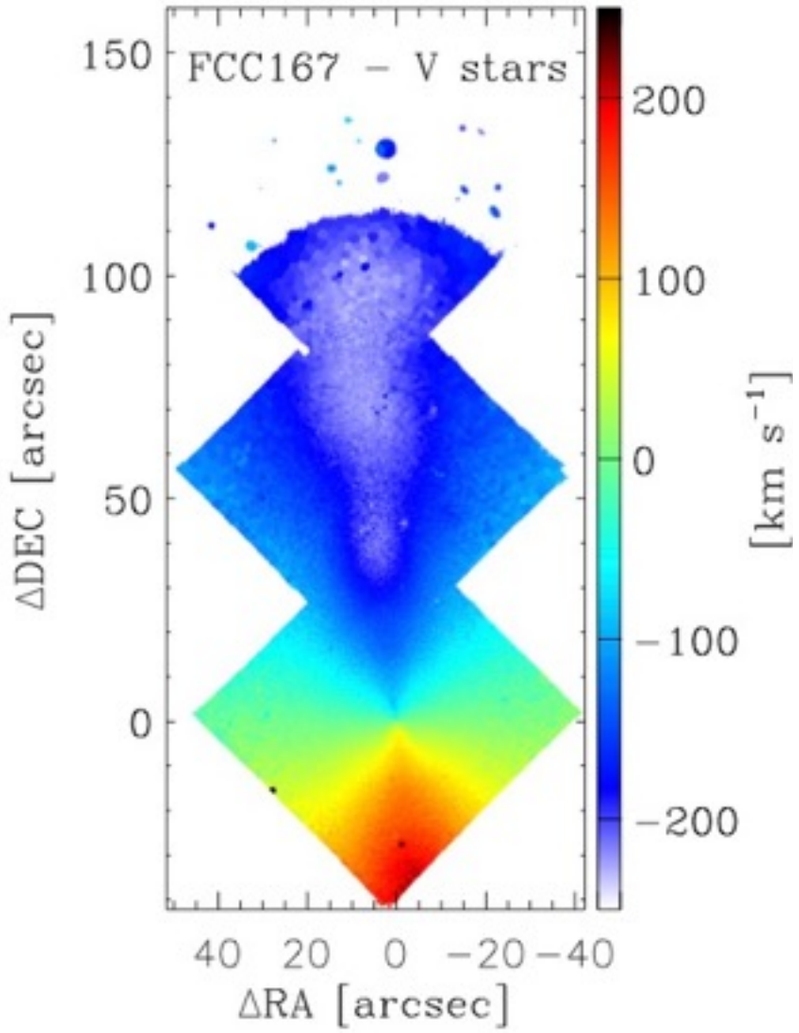
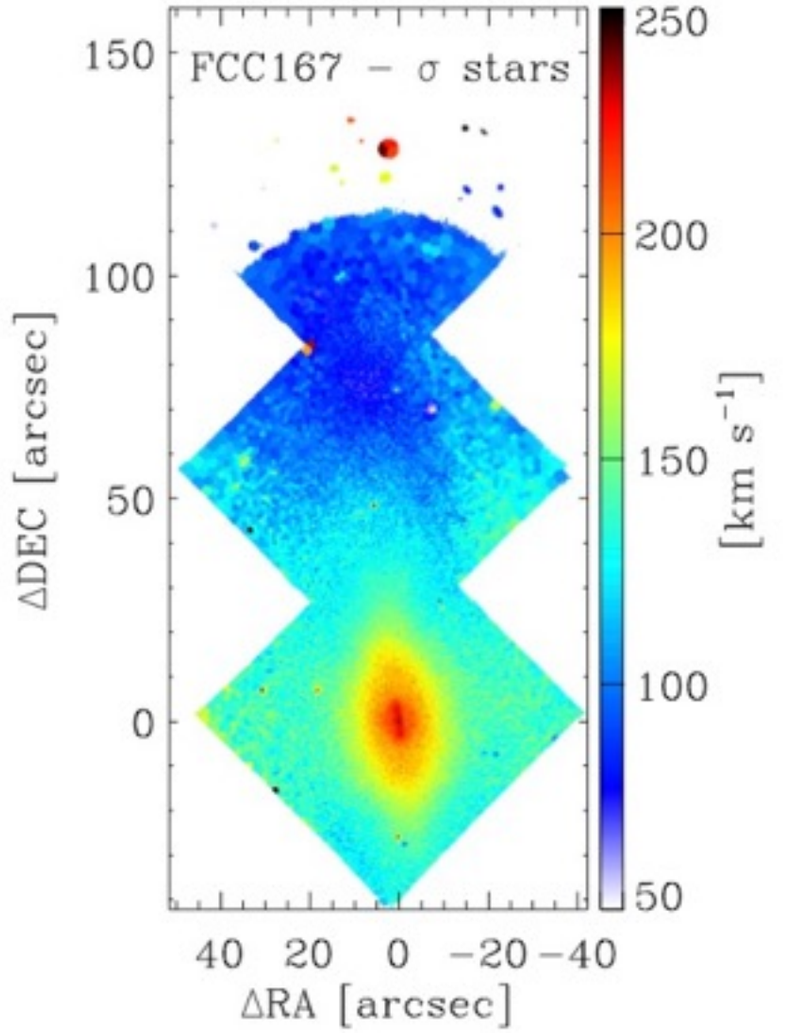
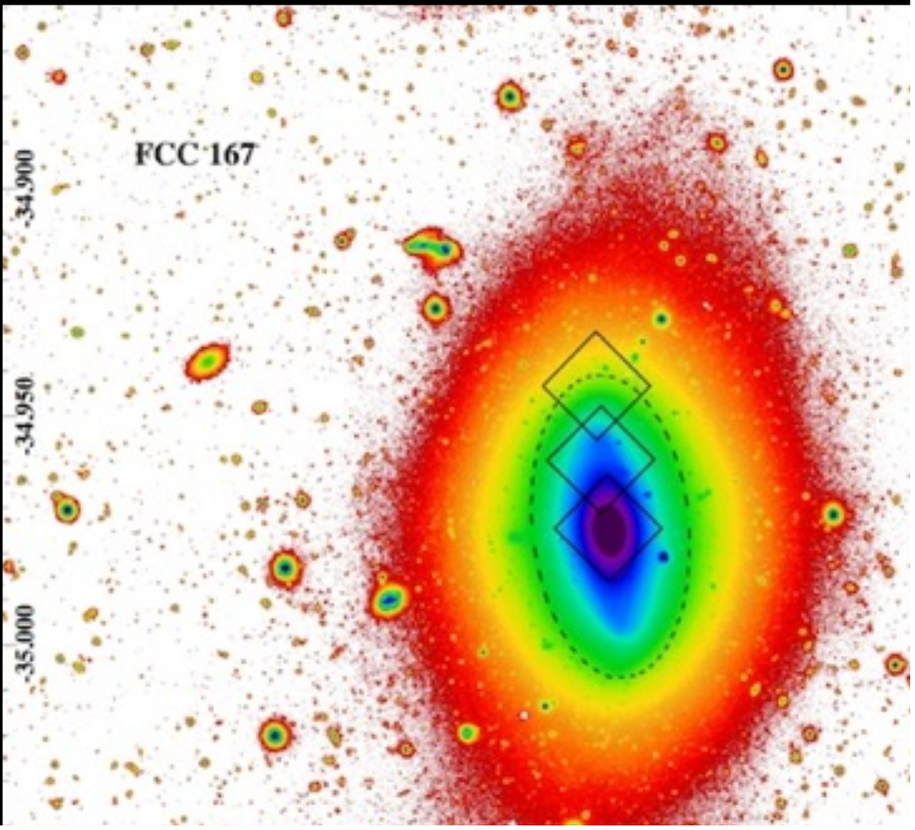


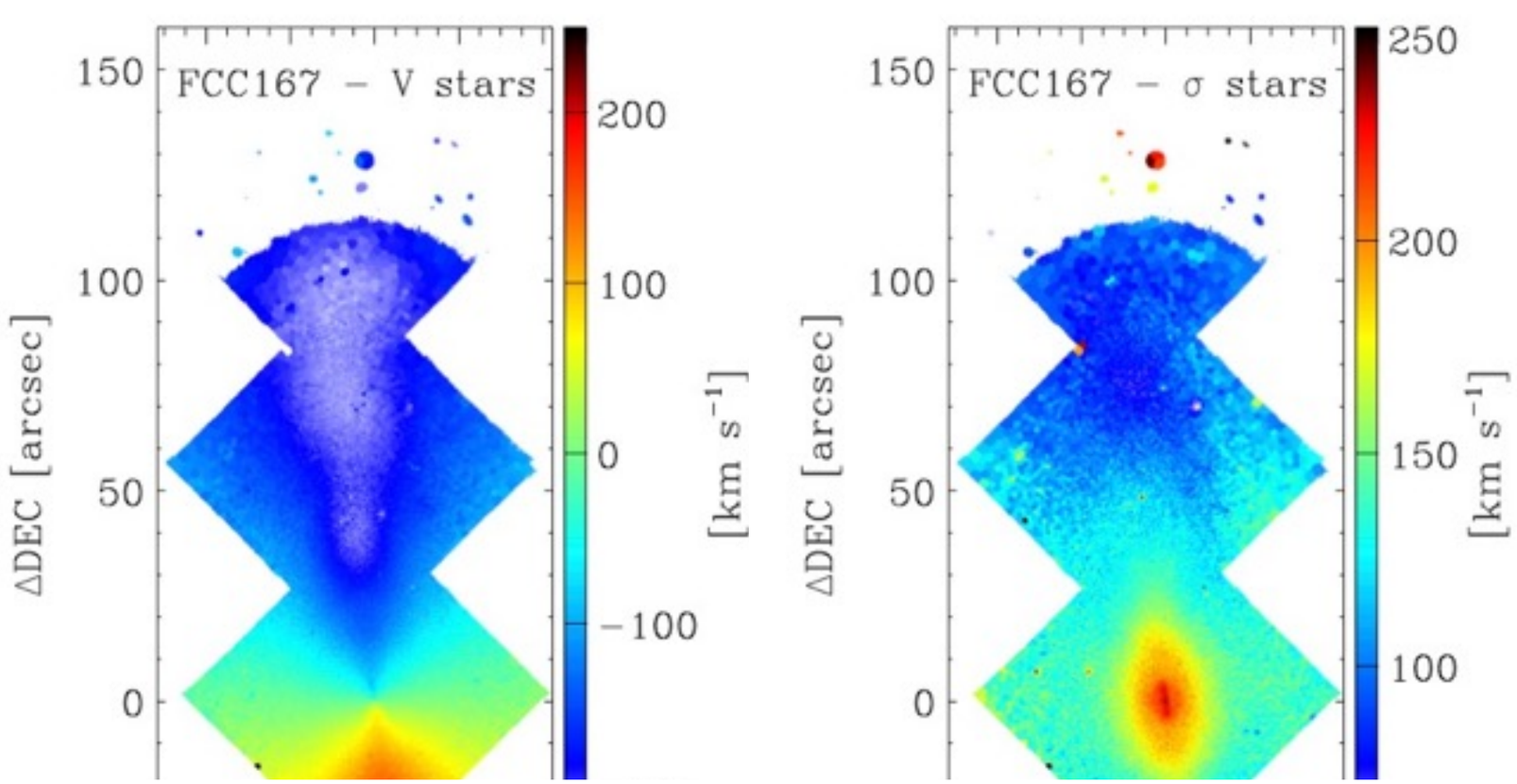


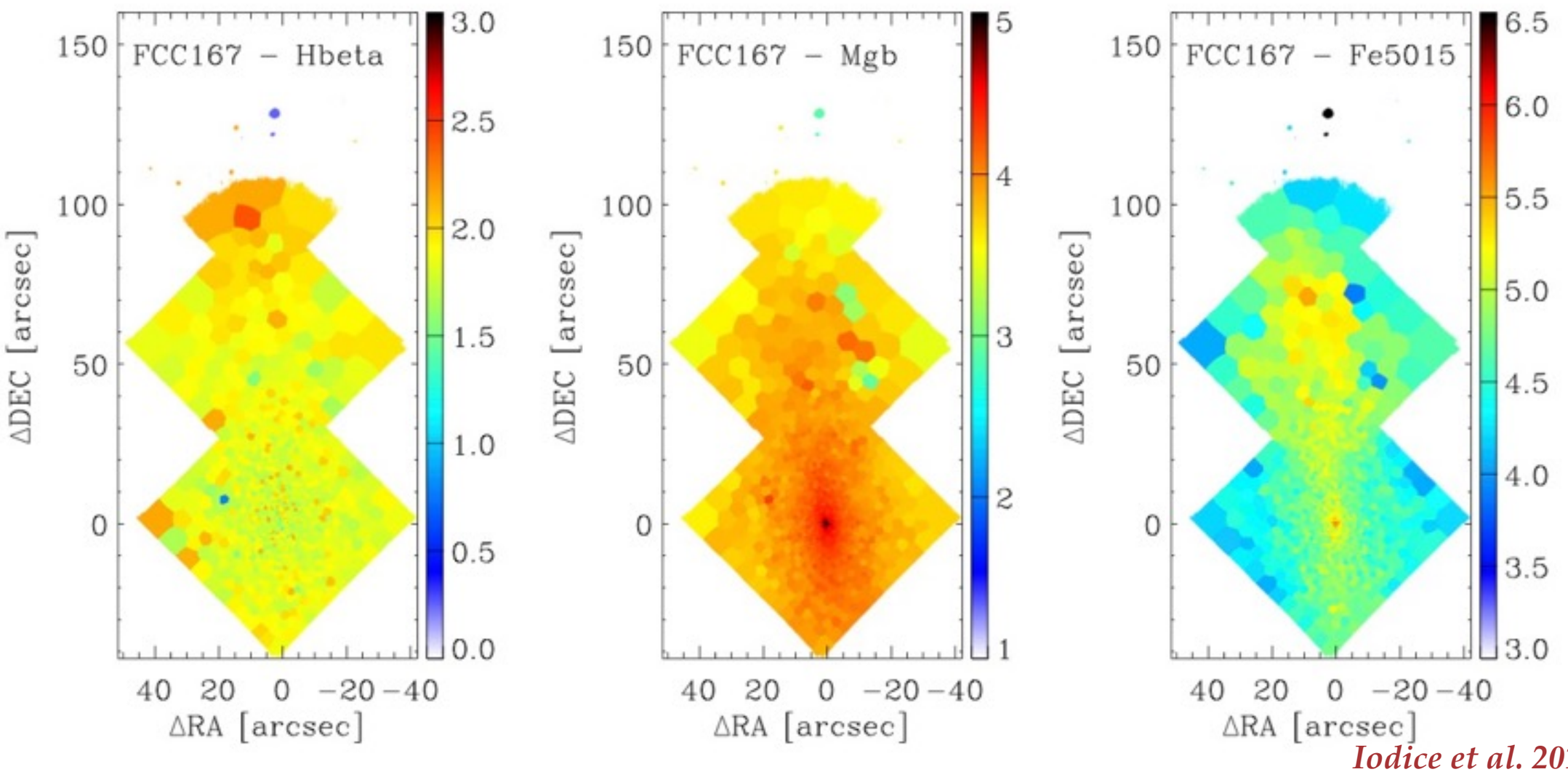


Fornax3D results: kinematics + LS maps + ionised-gas emission

Iodice et al. 2019, A&A accepted







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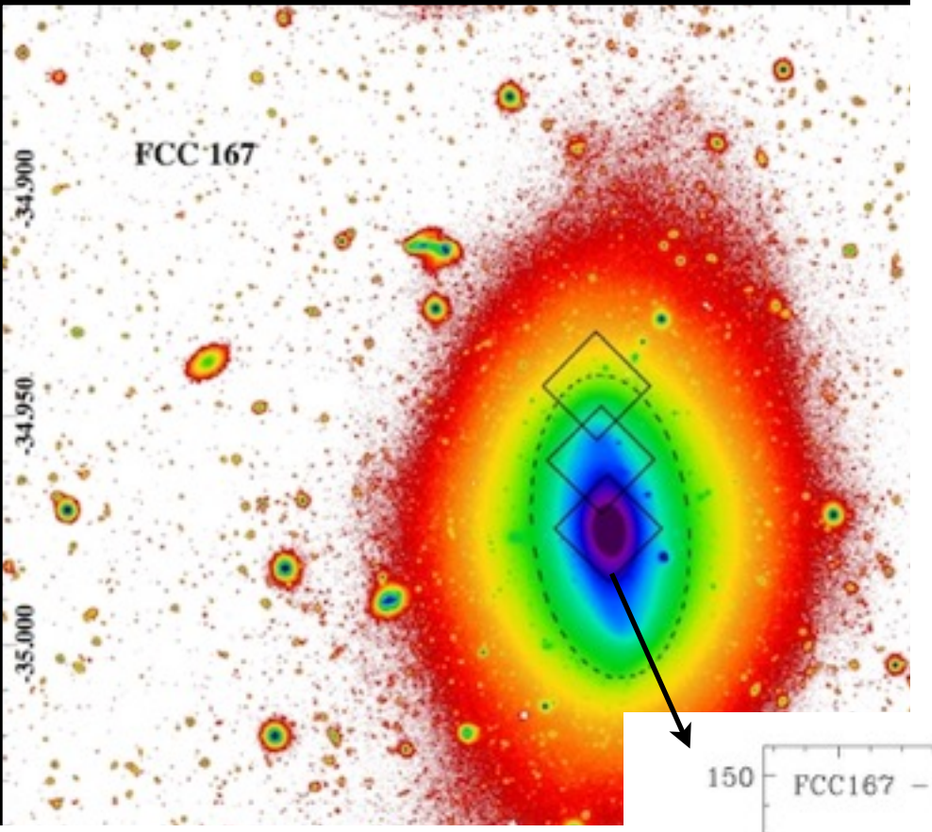
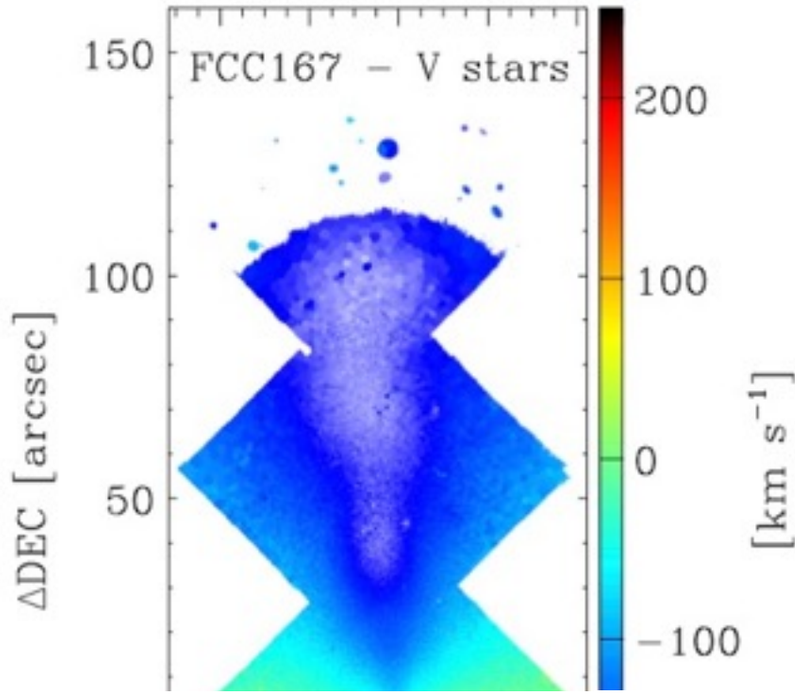
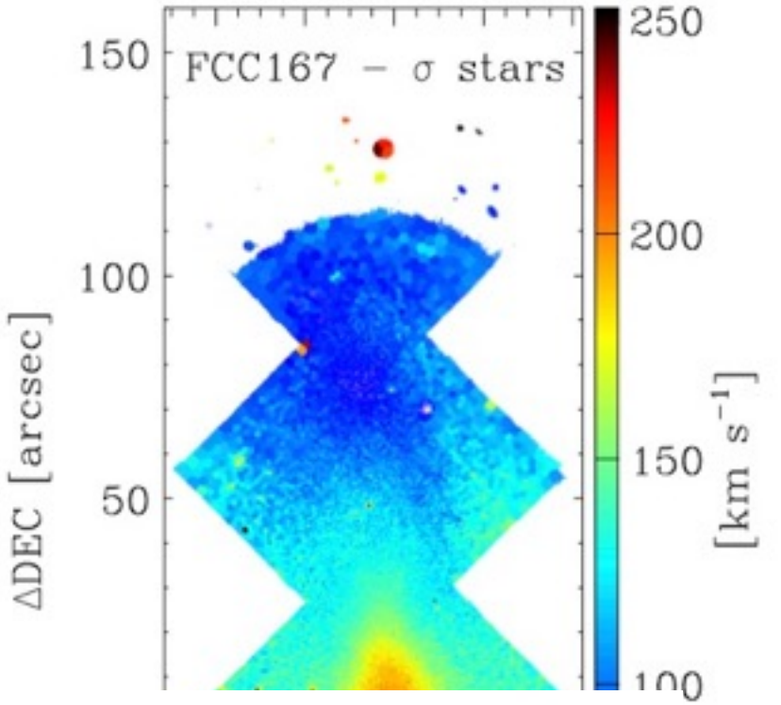
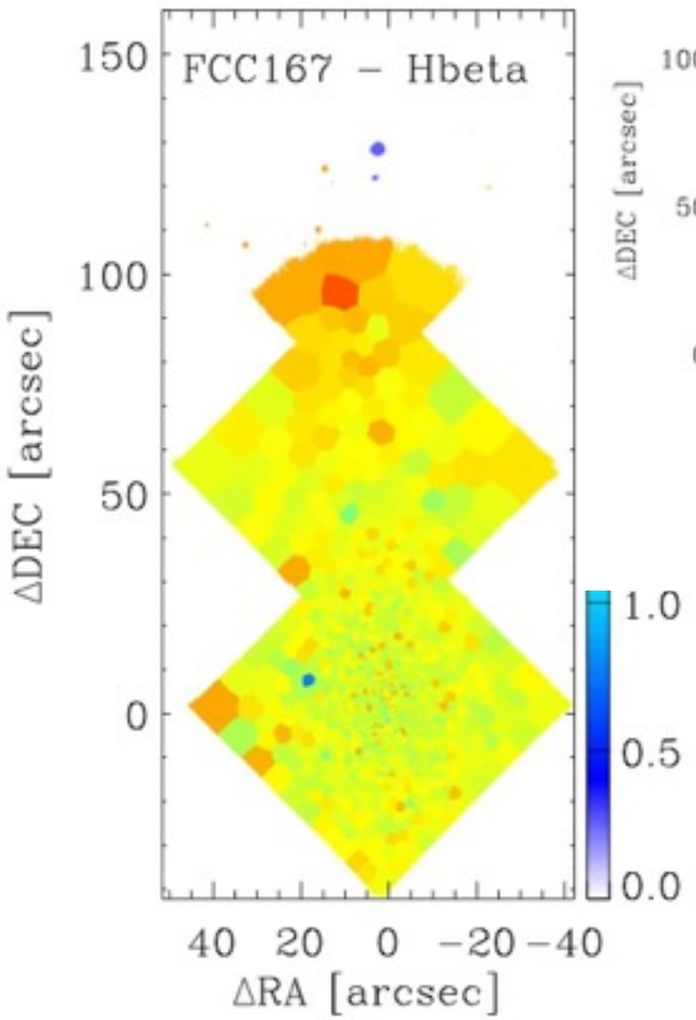
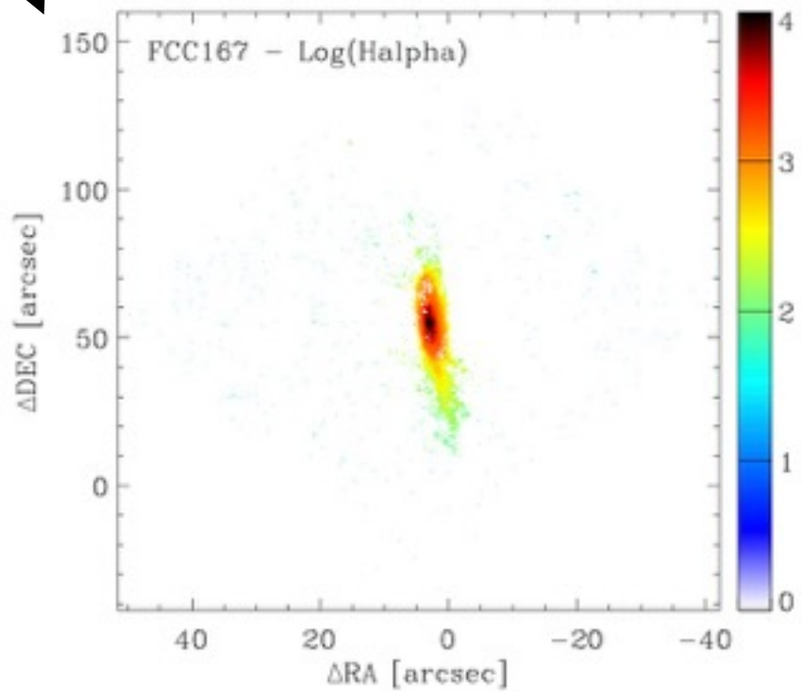
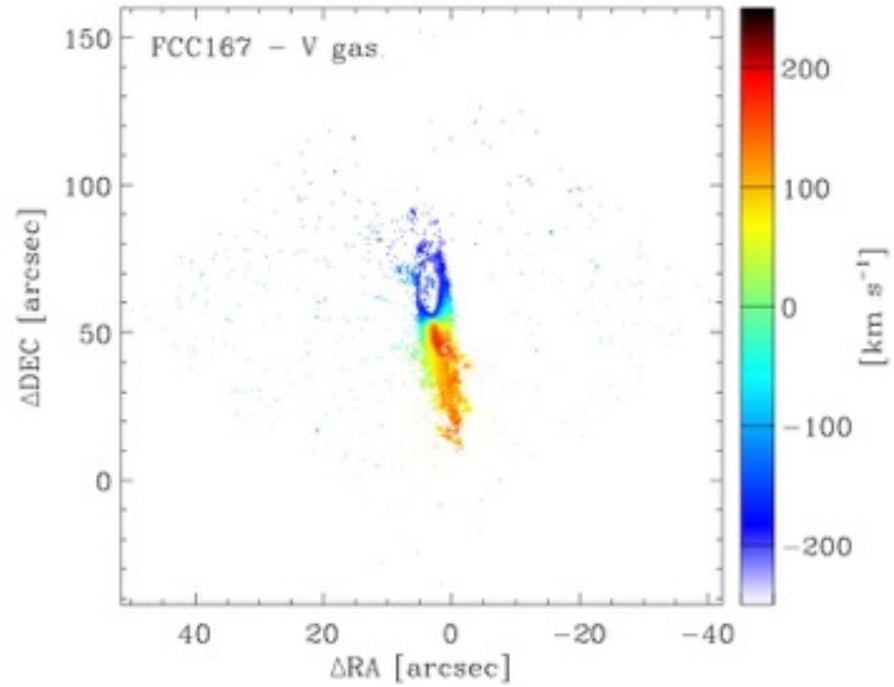


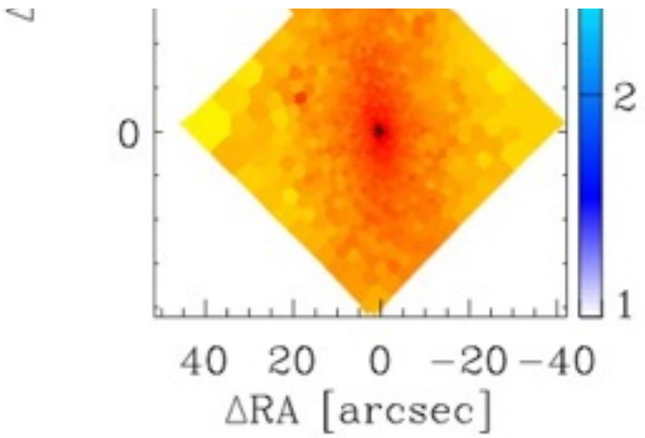


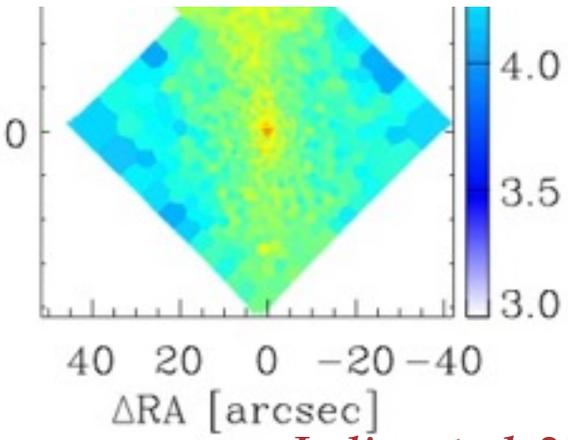












Iodice et al. 2019, A&A accepted

what next from F3D?
FDS *vs* F3D

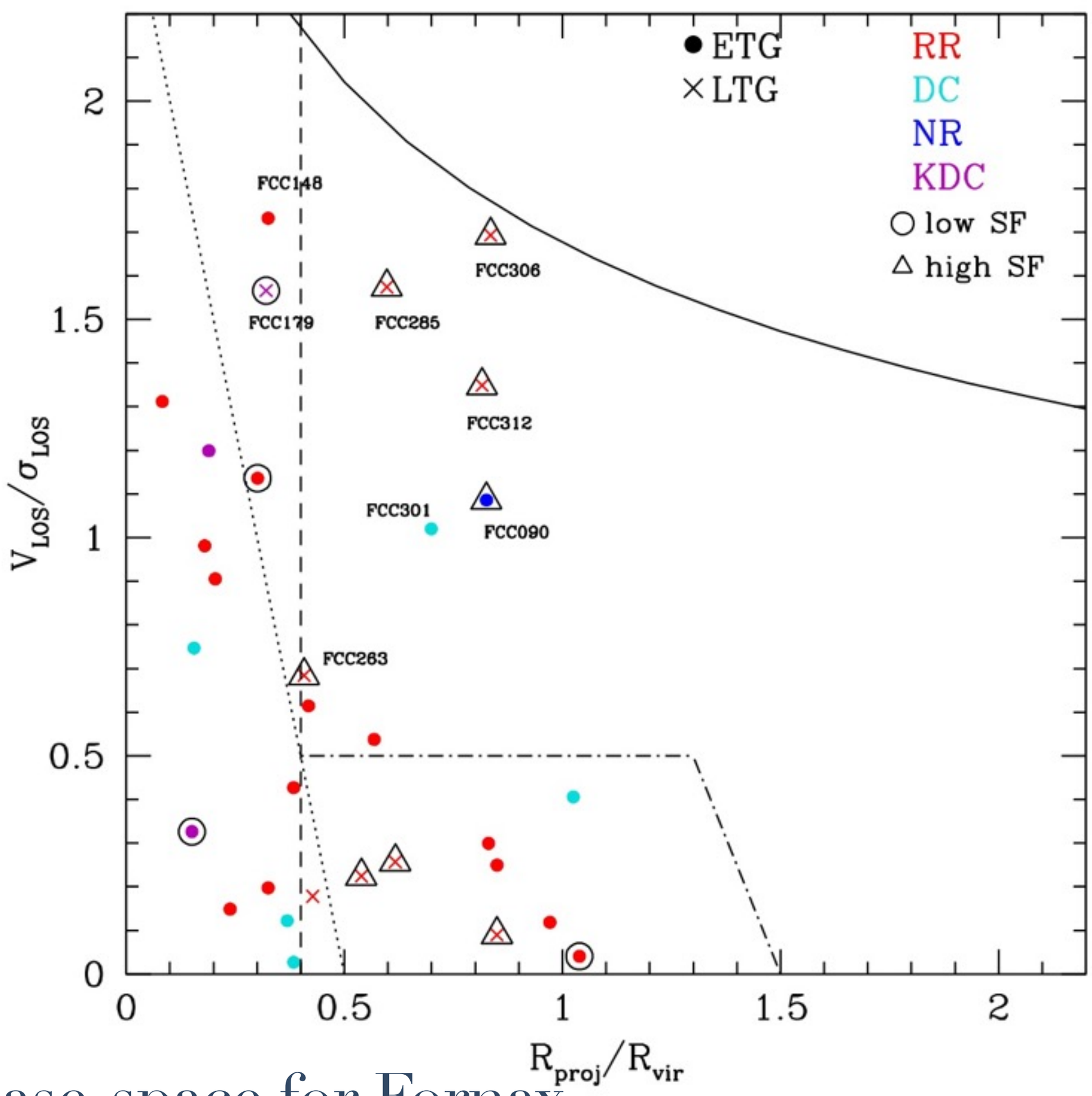
map the structure of galaxies (kinematics & SP) to trace the assembly history of the cluster

The structure of the Fornax cluster has been traced by combining the 2D distribution of the sample galaxies with the phase-space information

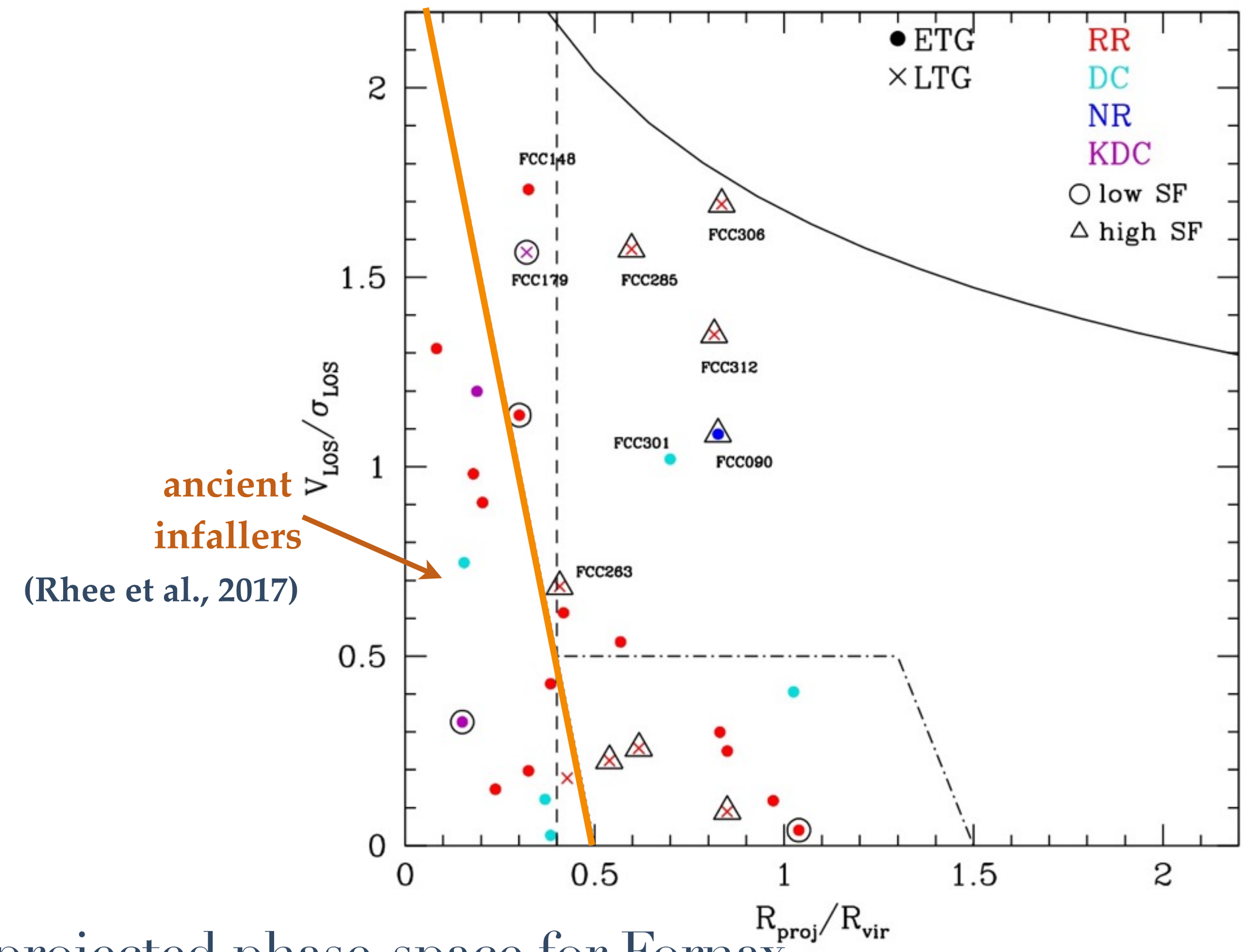
+

with the structural properties of the galaxies (morphology, colors, kinematics and stellar population)

Iodice et al. 2019, A&A, accepted



projected phase-space for Fornax

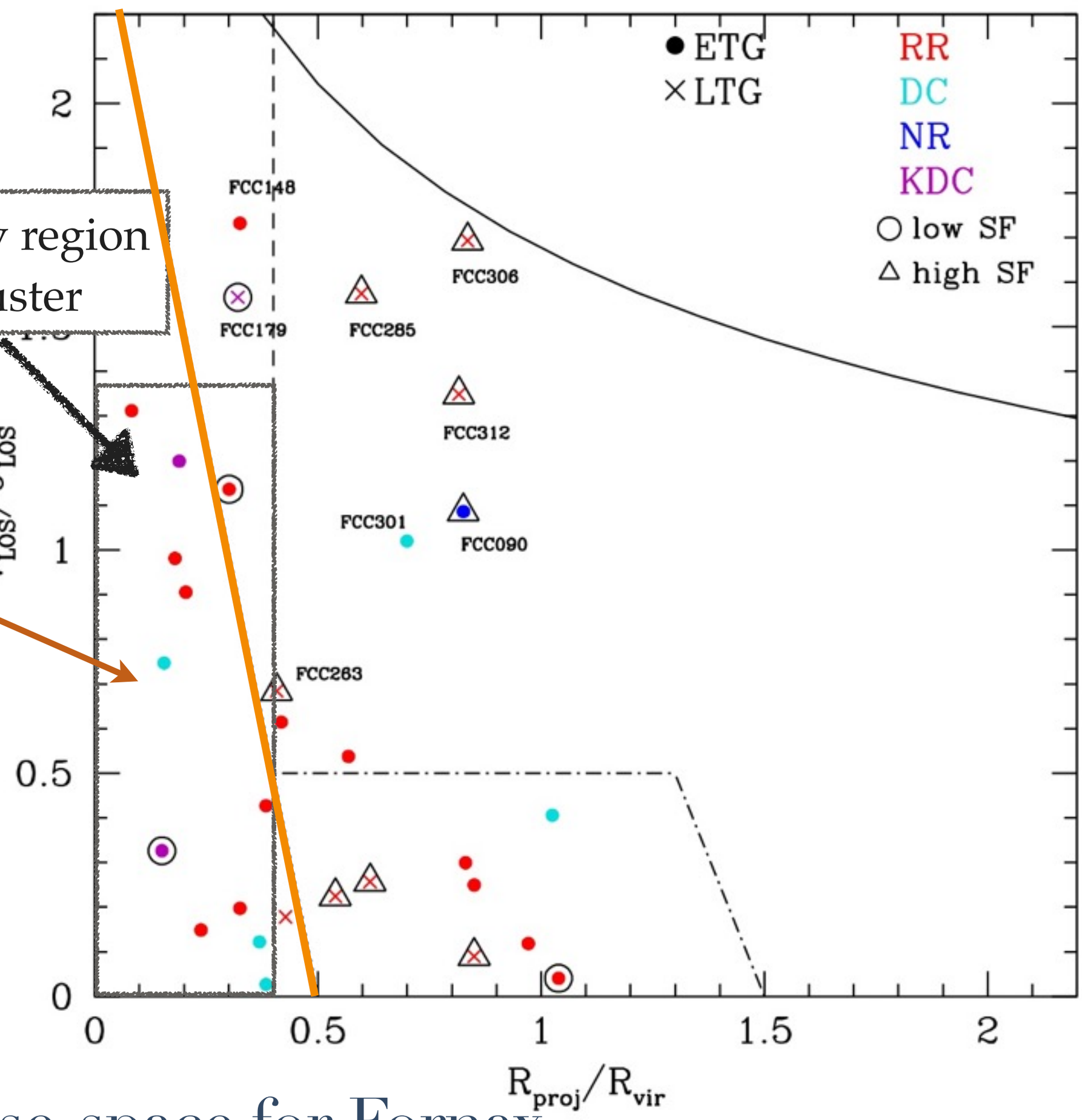


projected phase-space for Fornax

high-density region of the cluster

ancient infallers

(Rhee et al., 2017)



projected phase-space for Fornax

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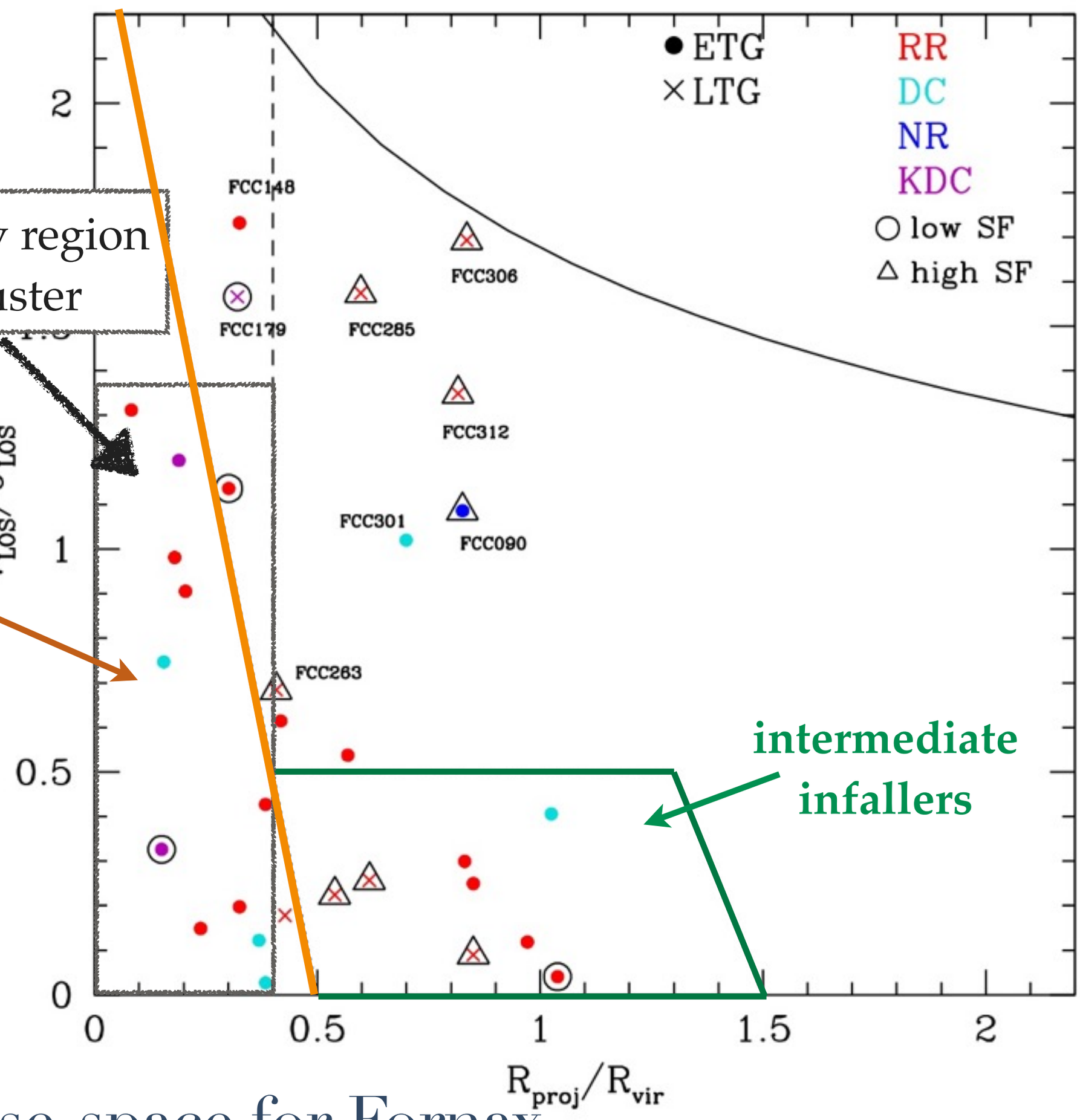
intermediate infallers



projected phase-space for Fornax

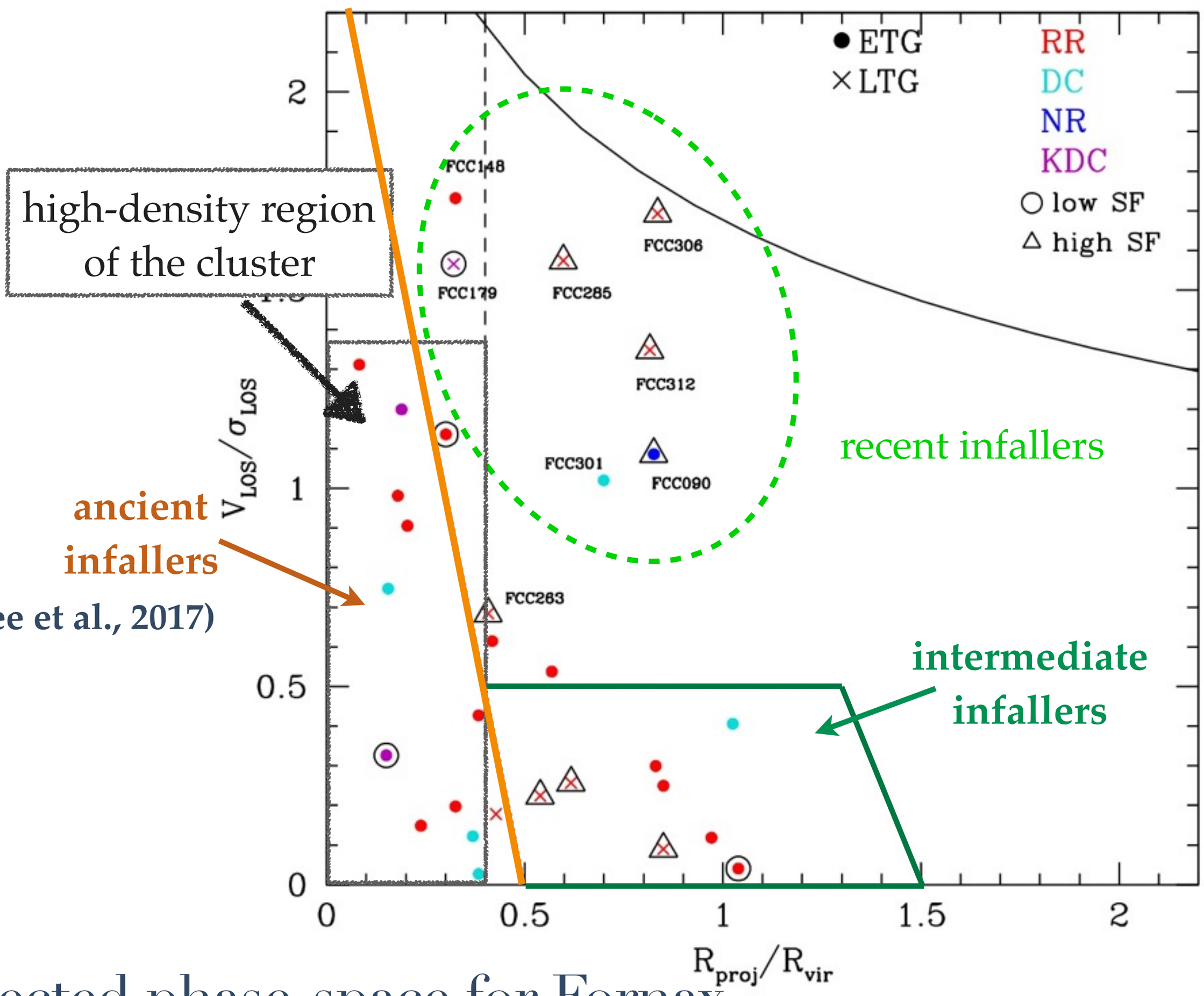
high-density region of the cluster

ancient infallers

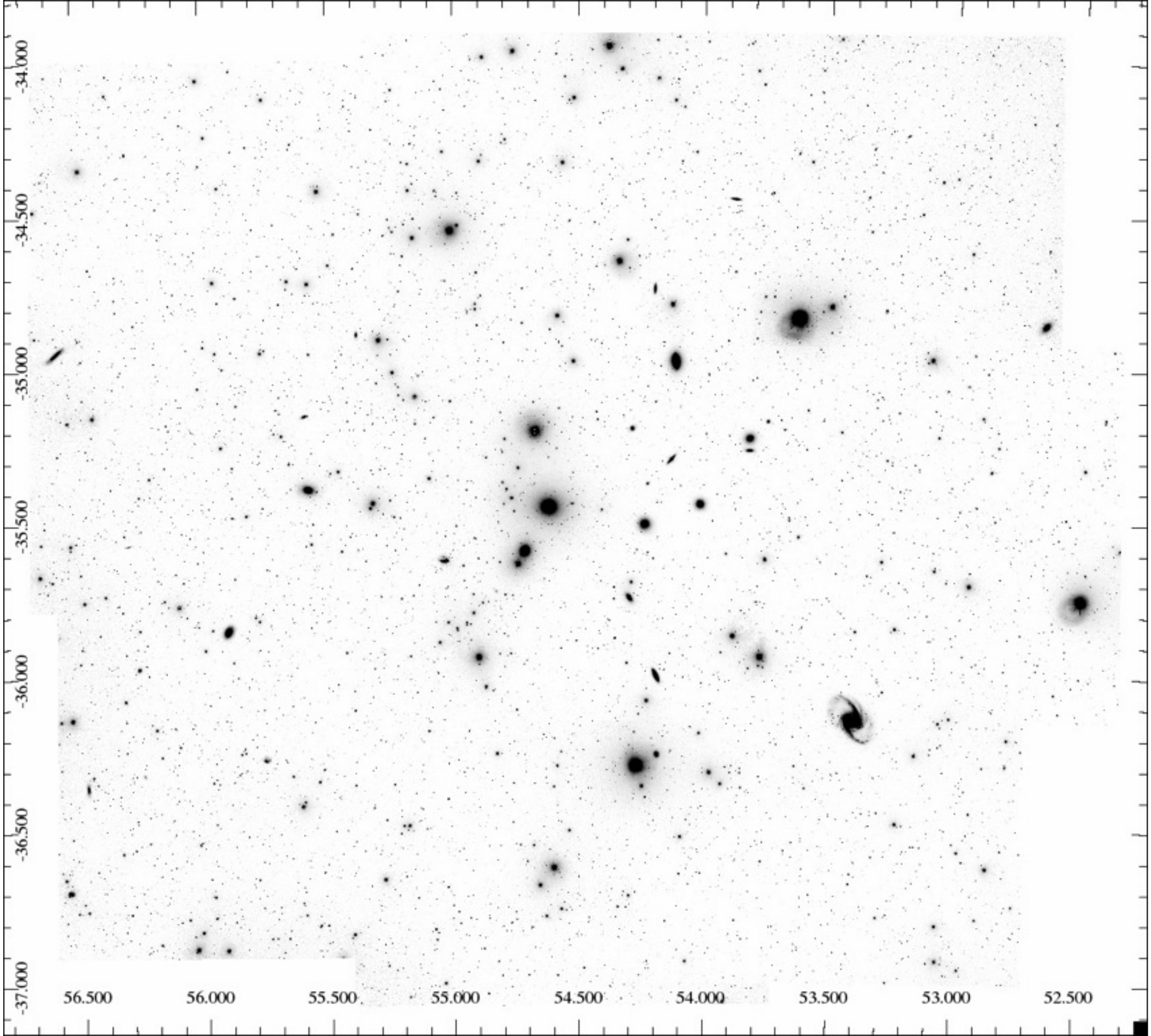
(Rhee et al., 2017)

recent infallers

intermediate infallers



projected phase-space for Fornax


ETG
LTG
-34.000
-34.500
-35.000
-35.500
-36.000
-36.500
-37.000
56.500
56.000
55.500
55.000
54.500
54.000
53.500
53.000
52.500

ancient infallers

ETG
LTG

-34.000
-34.500
-35.000
-35.500
-36.000
-36.500
-37.000

56.500
56.000
55.500
55.000
54.500
54.000
53.500
53.000
52.500

ancient infallers

ETG

LTG

SR

-34.000

-34.500

-35.000

-35.500

-36.000

-36.500

-37.000

56.500

56.000

55.500

55.000

54.500

54.000

53.500

53.000

52.500

ancient infallers

intermediate infallers

ETG

LTG

SR

-34.000
-34.500
-35.000
-35.500
-36.000
-36.500
-37.000

56.500
56.000
55.500
55.000
54.500
54.000
53.500
53.000
52.500

ancient infallers

intermediate infallers

recent infallers

ETG

LTG

SR

-34.000
-34.500
-35.000
-35.500
-36.000
-36.500
-37.000

56.500
56.000
55.500
55.000
54.500
54.000
53.500
53.000
52.500

ancient infallers

intermediate infallers

recent infallers

N-S clump

ETG

LTG

SR

-34.000
-34.500
-35.000
-35.500
-36.000
-36.500
-37.000

56.500
56.000
55.500
55.000
54.500
54.000
53.500
53.000
52.500

ancient infallers

intermediate infallers

recent infallers

N-S clump

infalling galaxies

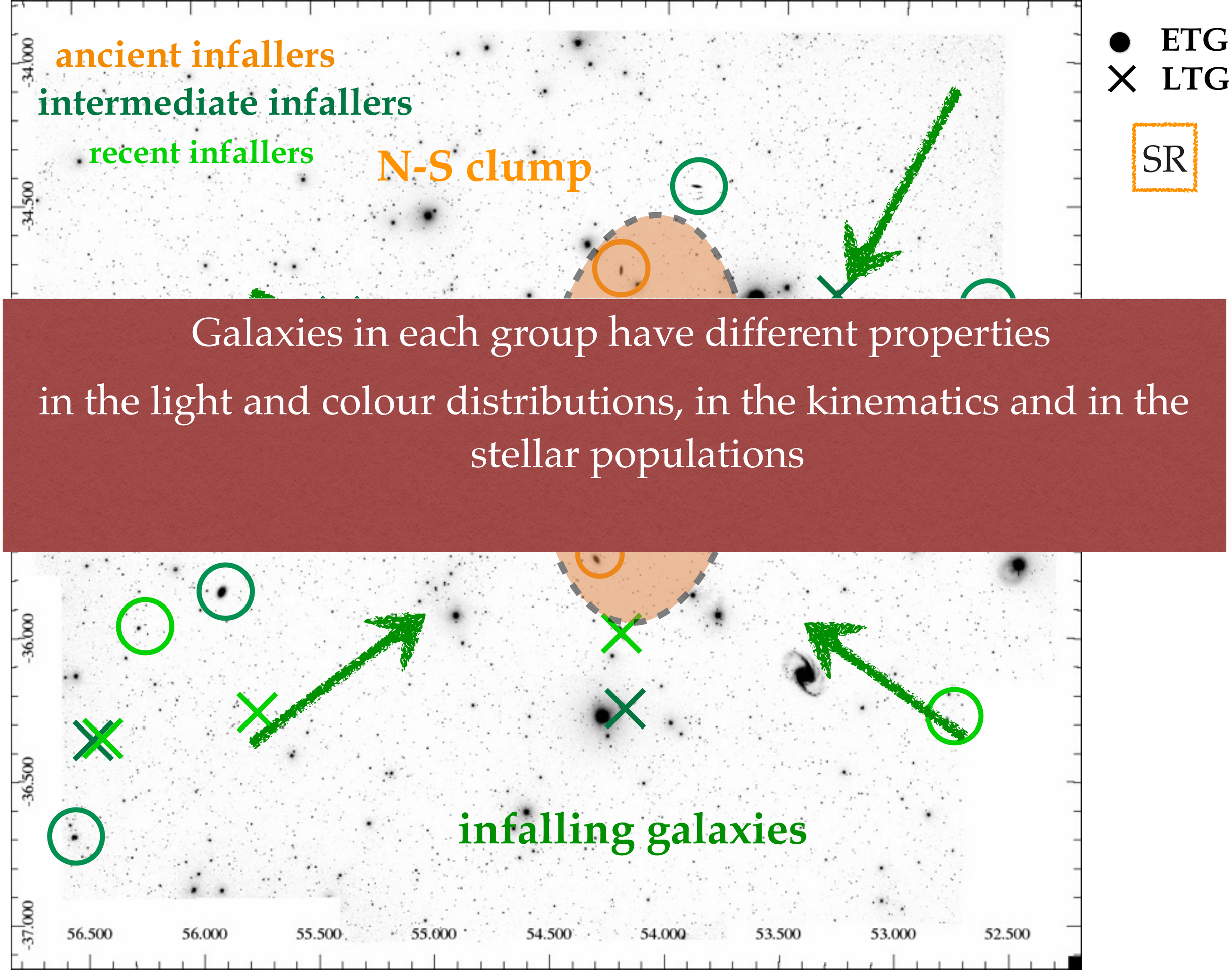
ETG

LTG

SR

-34.000
-34.500
-35.000
-35.500
-36.000
-36.500
-37.000

56.500
56.000
55.500
55.000
54.500
54.000
53.500
53.000
52.500



Galaxies in each group have different properties

in the light and colour distributions, in the kinematics and in the stellar populations

ancient infallers

intermediate infallers

recent infallers

ETG

LTG

SR

-34.000
-34.500
-35.000
-35.500
-36.000
-36.500
-37.000

56.500
56.000
55.500
55.000
54.500
54.000
53.500
53.000
52.500

ancient infallers

intermediate infallers

recent infallers

ETG

LTG

SR

low SF in the center

-34.000
-34.500
-35.000
-35.500
-36.000
-36.500
-37.000

56.500
56.000
55.500
55.000
54.500
54.000
53.500
53.000
52.500

ancient infallers

intermediate infallers

recent infallers

ETG

LTG

SR

FCC184

low SF in the center

-34.000

-34.500

-35.000

54.500

54.000

53.500

53.000

52.500

Hα

V gas

ETG
LTG

SR

FCC184

low SF in the center

54.000 53.500 53.000 52.500

ancient infallers

intermediate infallers

recent infallers

ETG

LTG

infalling galaxies

-34.000
-34.500
-35.000
-35.500
-36.000
-36.500
-37.000

56.500
56.000
55.500
55.000
54.500
54.000
53.500
53.000
52.500

ancient infallers

intermediate infallers

recent infallers

high SF

ETG

LTG

infalling galaxies

-34.000
-34.500
-35.000
-35.500
-36.000
-36.500
-37.000

56.500
56.000
55.500
55.000
54.500
54.000
53.500
53.000
52.500

FCC285

high SF

ETG

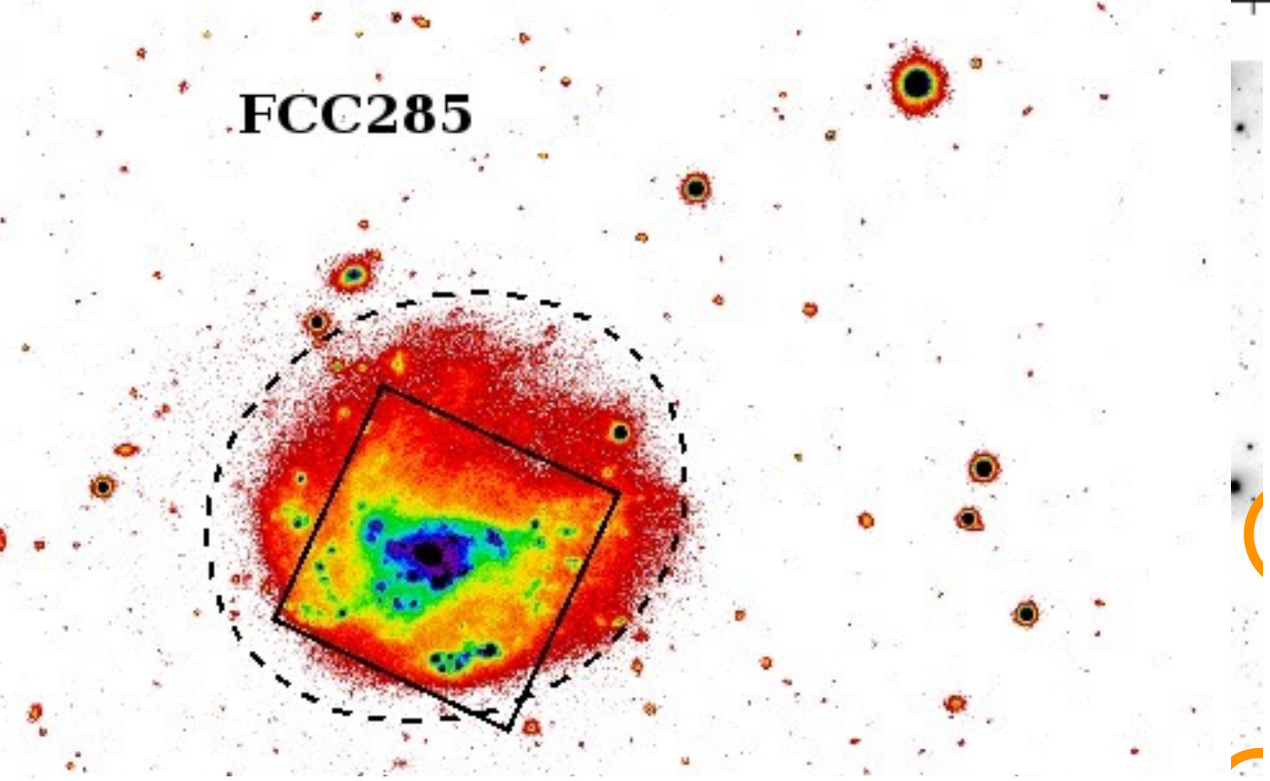
LTG

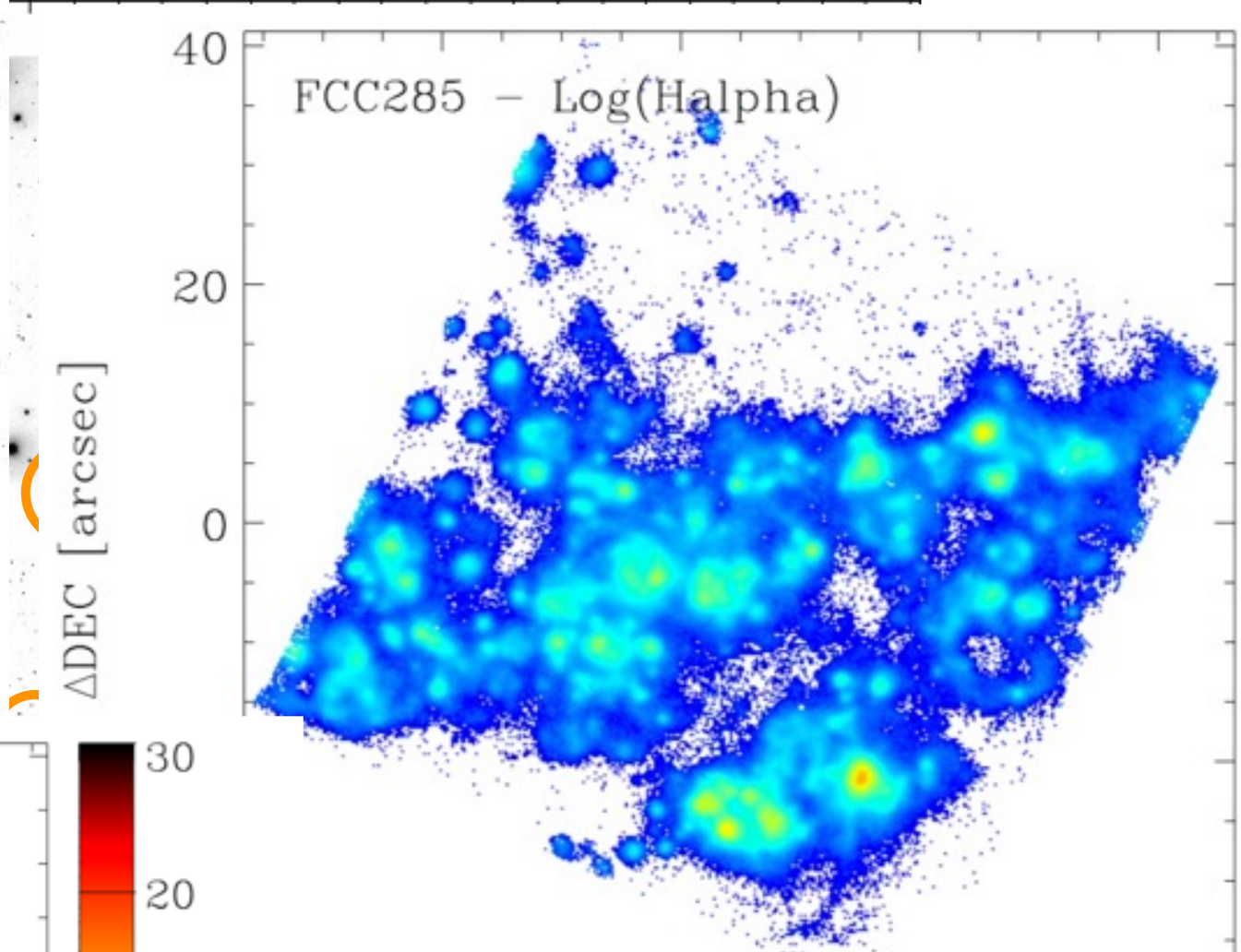
infalling galaxies

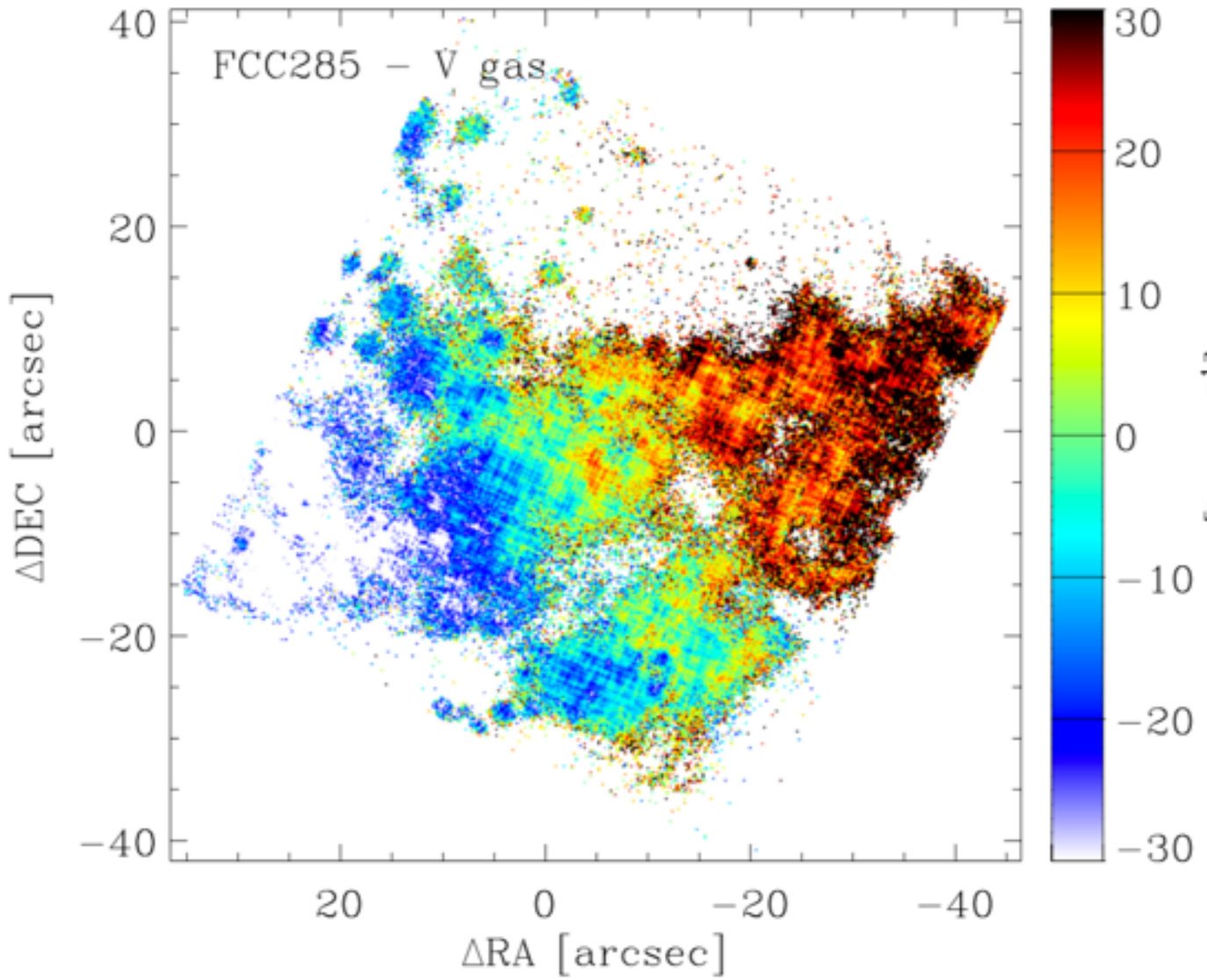
-36.500

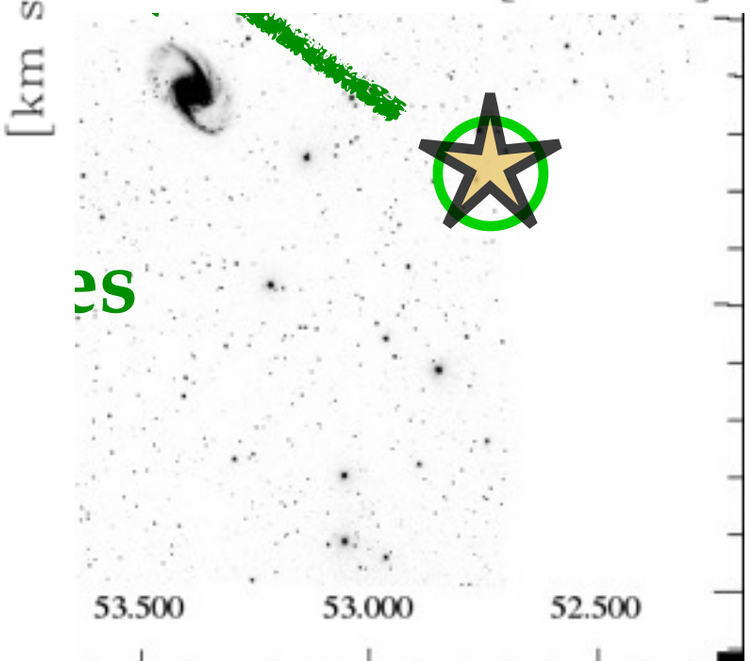
-37.000

56.500 56.000 55.500 55.000 54.500 54.000 53.500 53.000 52.500

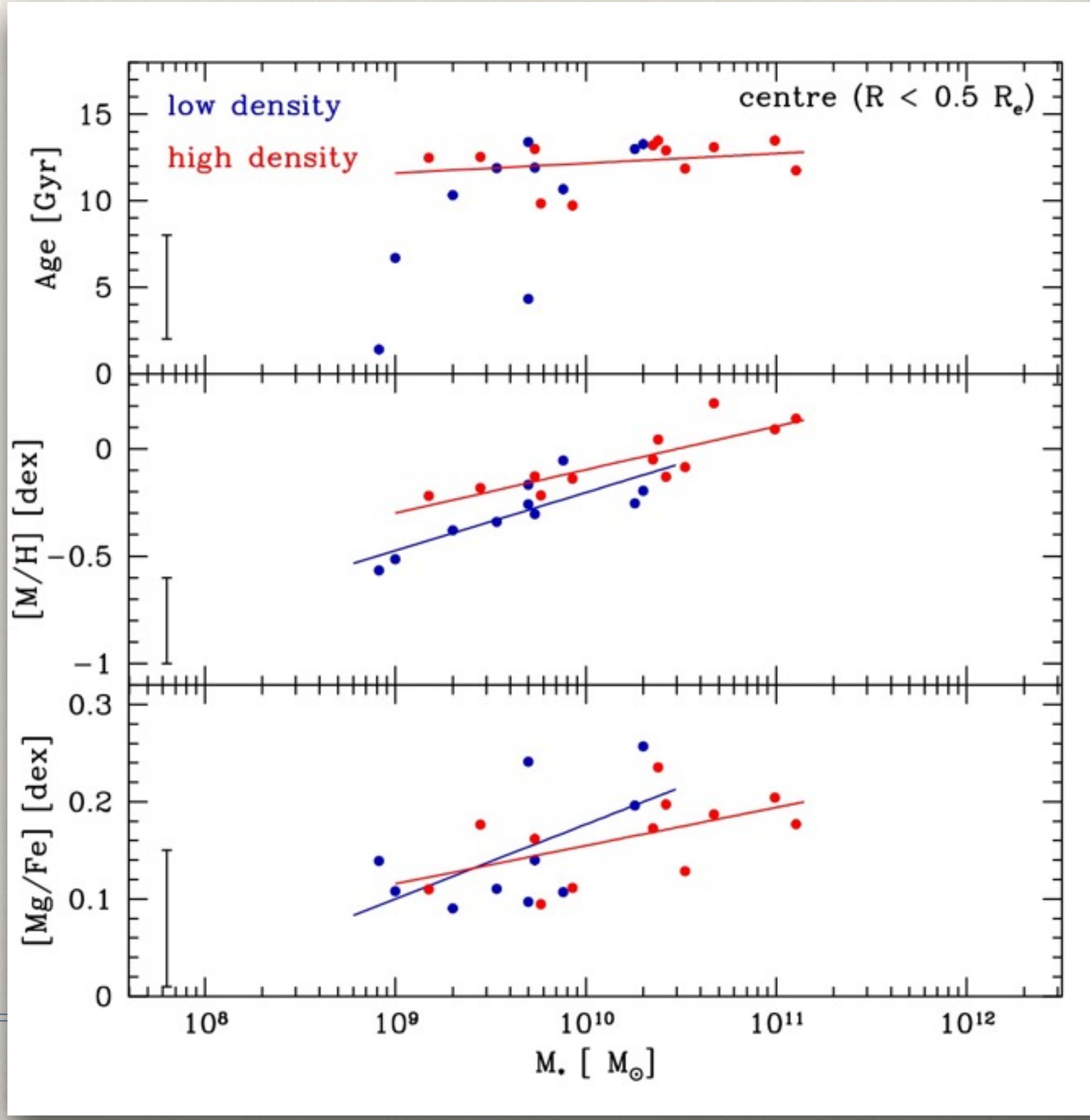

FCC285


FCC285 – Log(Halpha)
ΔDEC [arcsec]
ΔRA [arcsec]
40
20
0
−20
−40

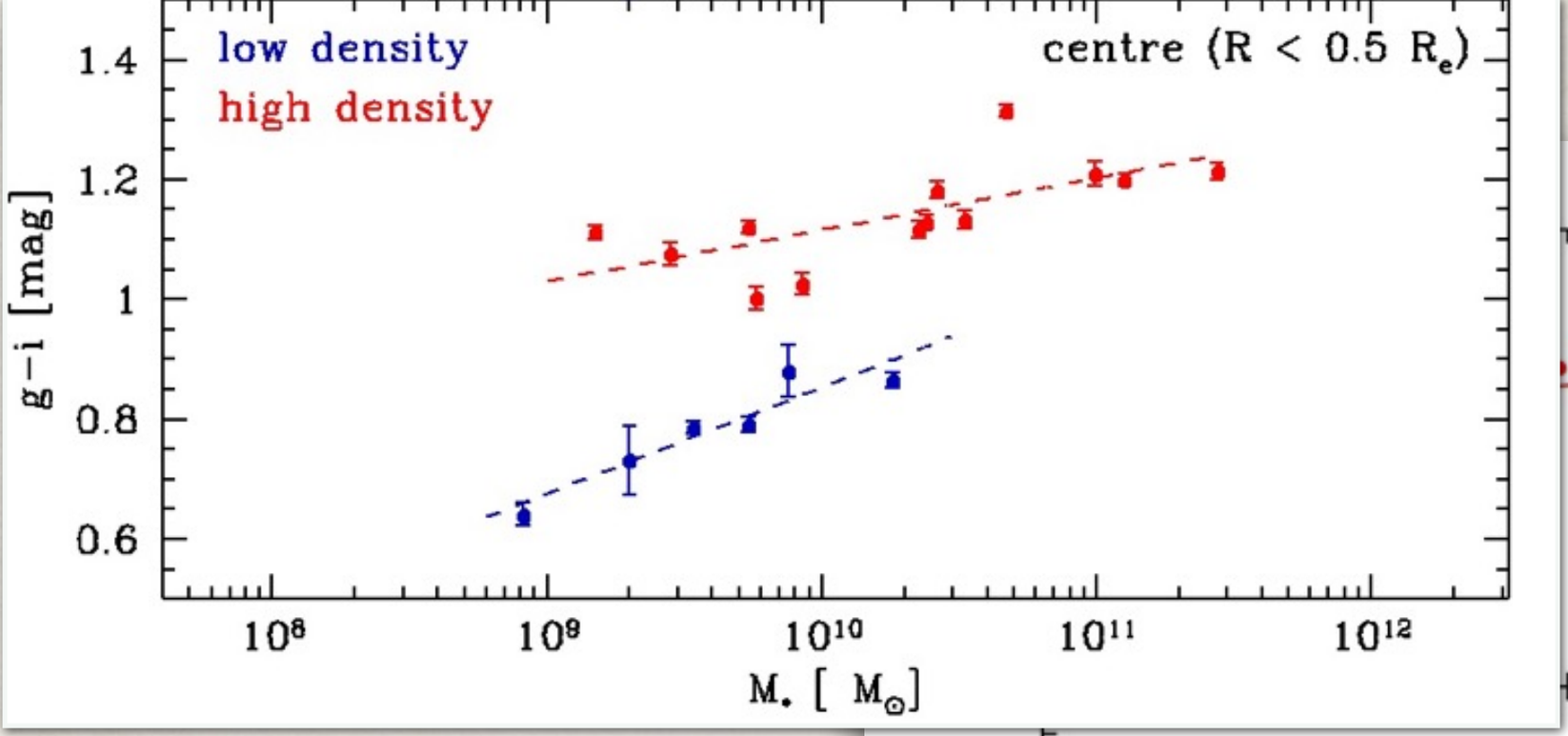

FCC285 – V gas
ΔDEC [arcsec]
ΔRA [arcsec]
[km s⁻¹]
30
20
10
0
−10
−20
−30
40
20
0
−20
−40

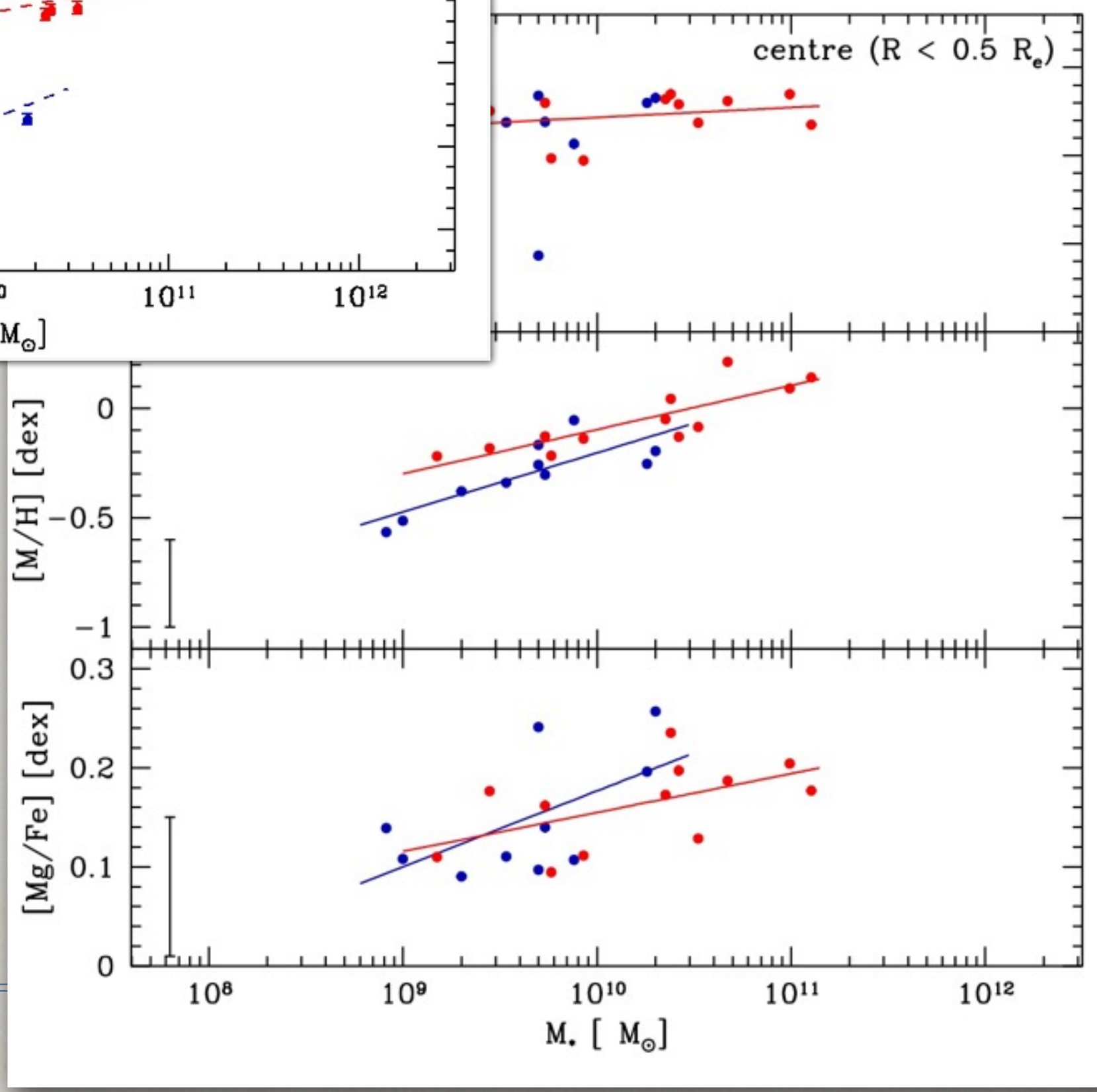

es
53.500
53.000
52.500

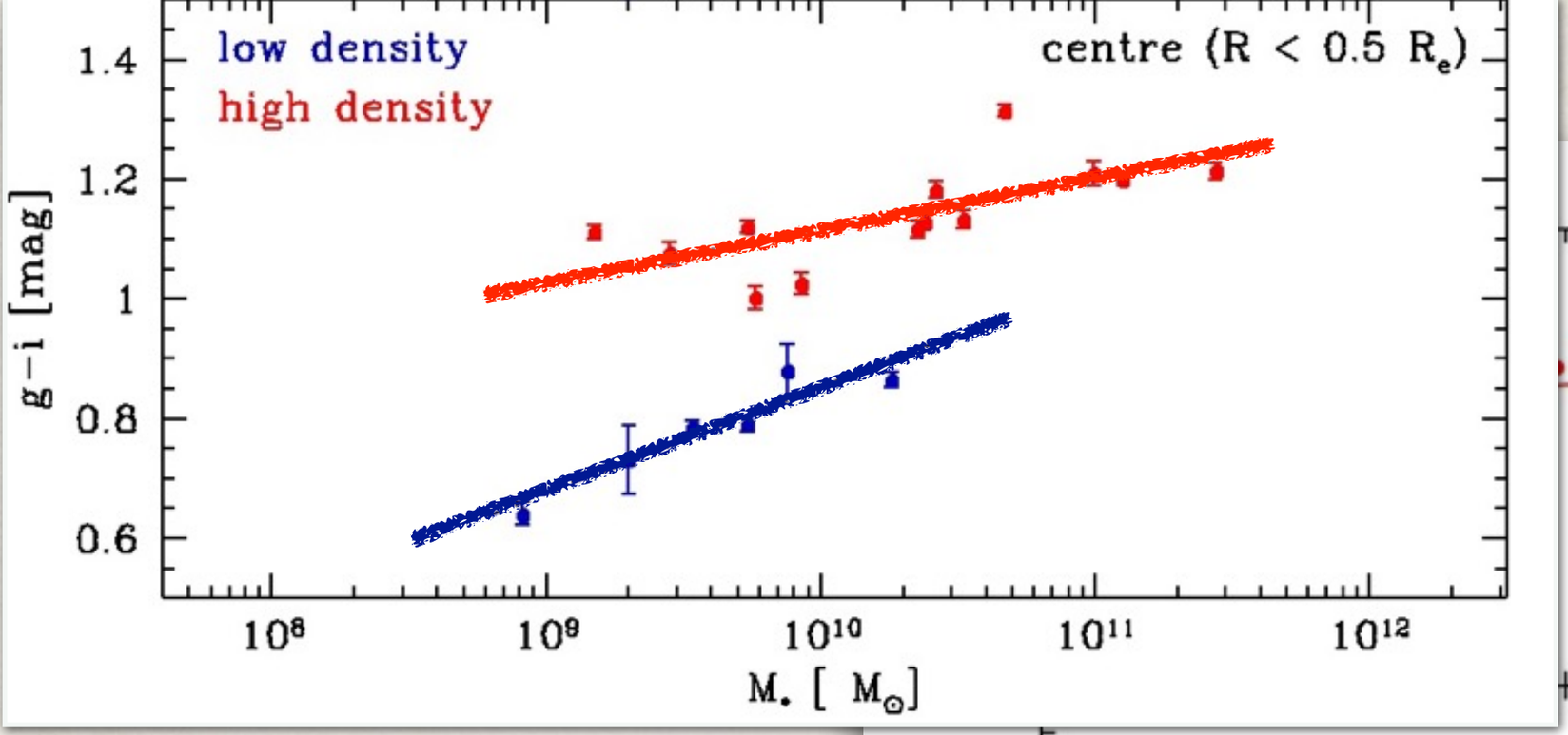
SP analysis

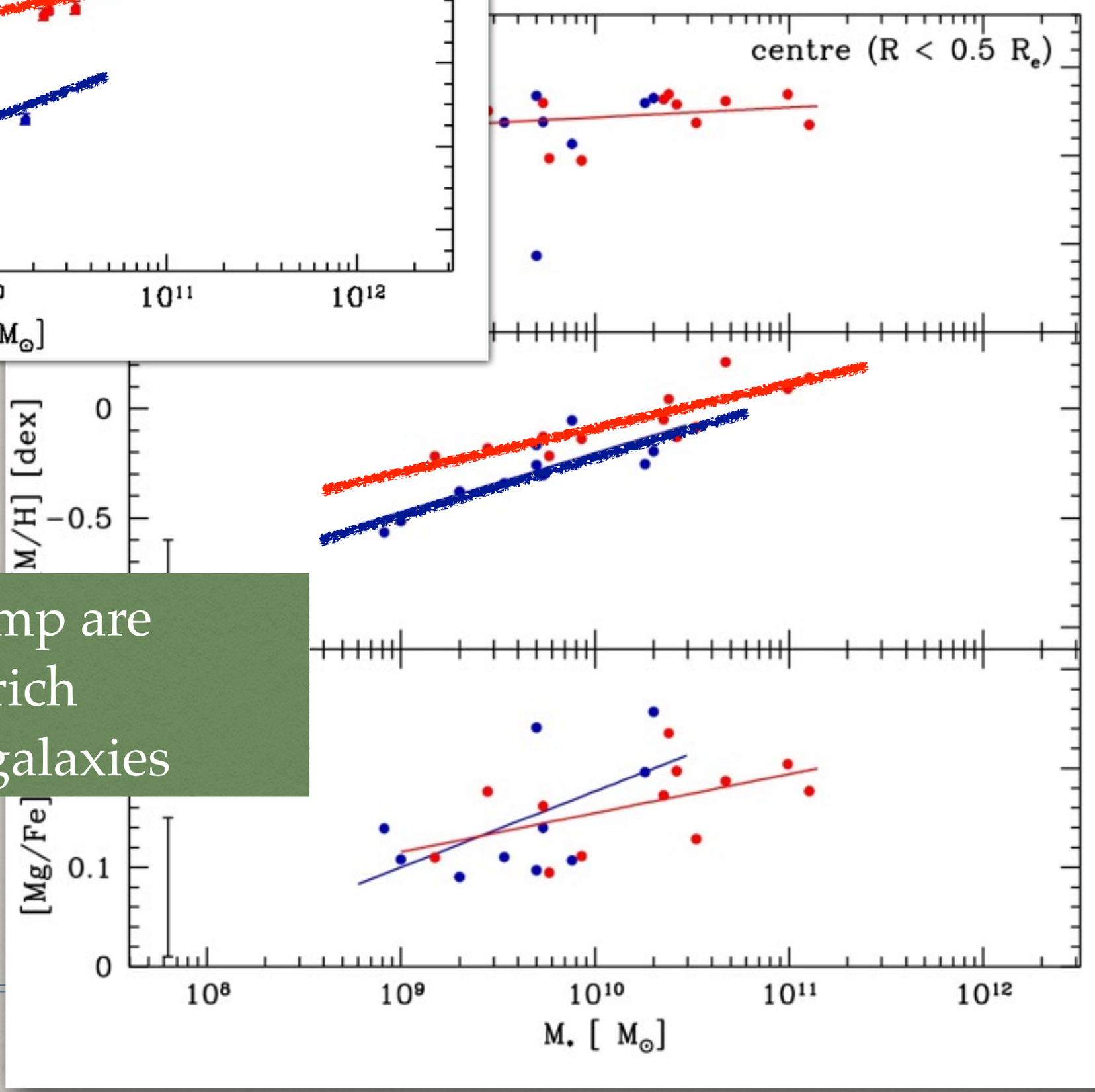

low density
high density
centre (R < 0.5 R_e)
Age [Gyr]
15
10
5
0
[M/H] [dex]
0
−0.5
−1
[Mg/Fe] [dex]
0.3
0.2
0.1
0
10^8
10^9
10^10
10^11
10^12
M* [M⊙]

SP analysis


low density
high density
centre (R < 0.5 R_e)
g−i [mag]
1.4
1.2
1
0.8
0.6
10^8
10^9
10^10
10^11
10^12
M* [M⊙]


centre (R < 0.5 R_e)
[M/H] [dex]
0
−0.5
−1
[Mg/Fe] [dex]
0.3
0.2
0.1
0
10^8
10^9
10^10
10^11
10^12
M* [M⊙]

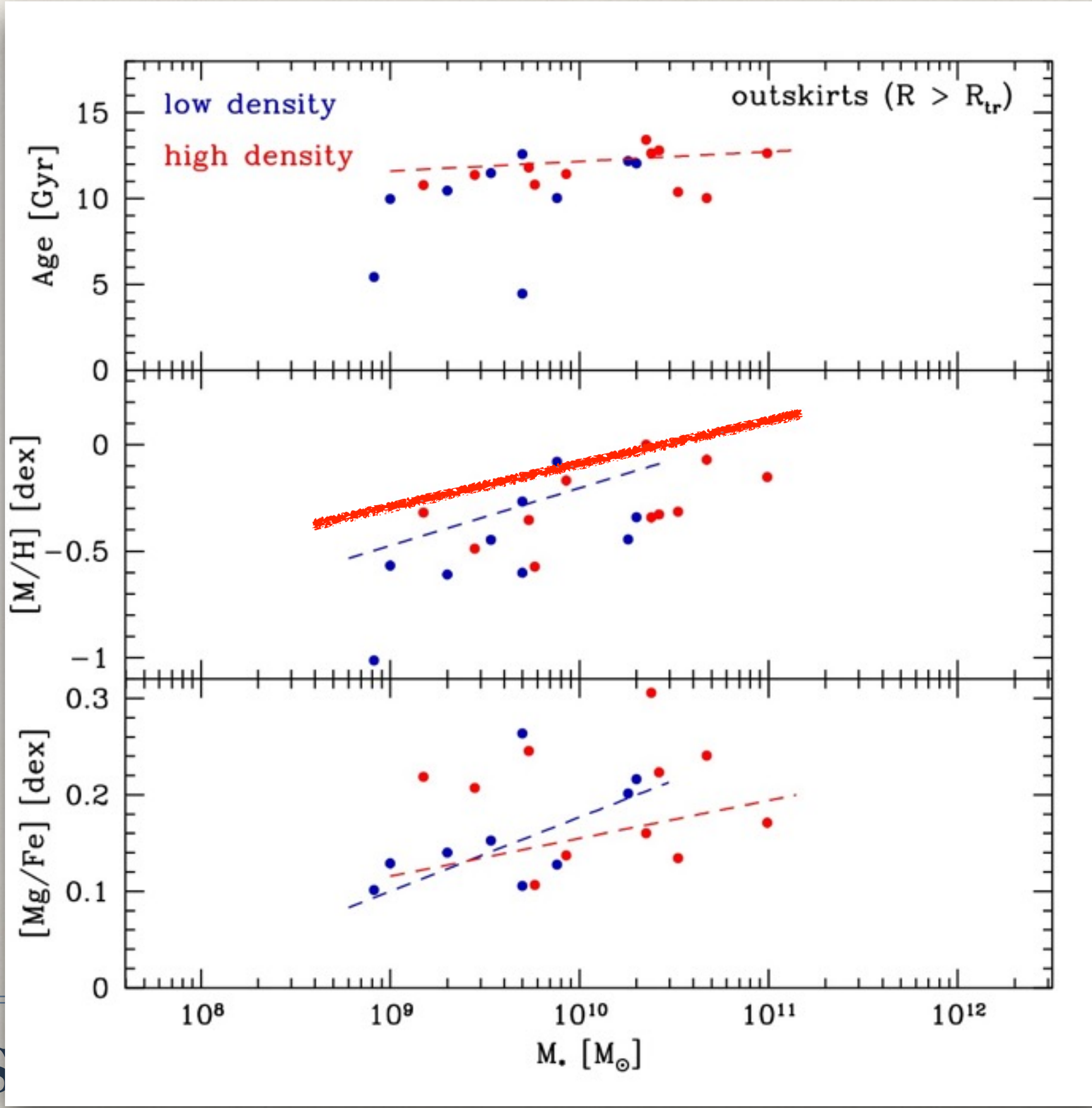




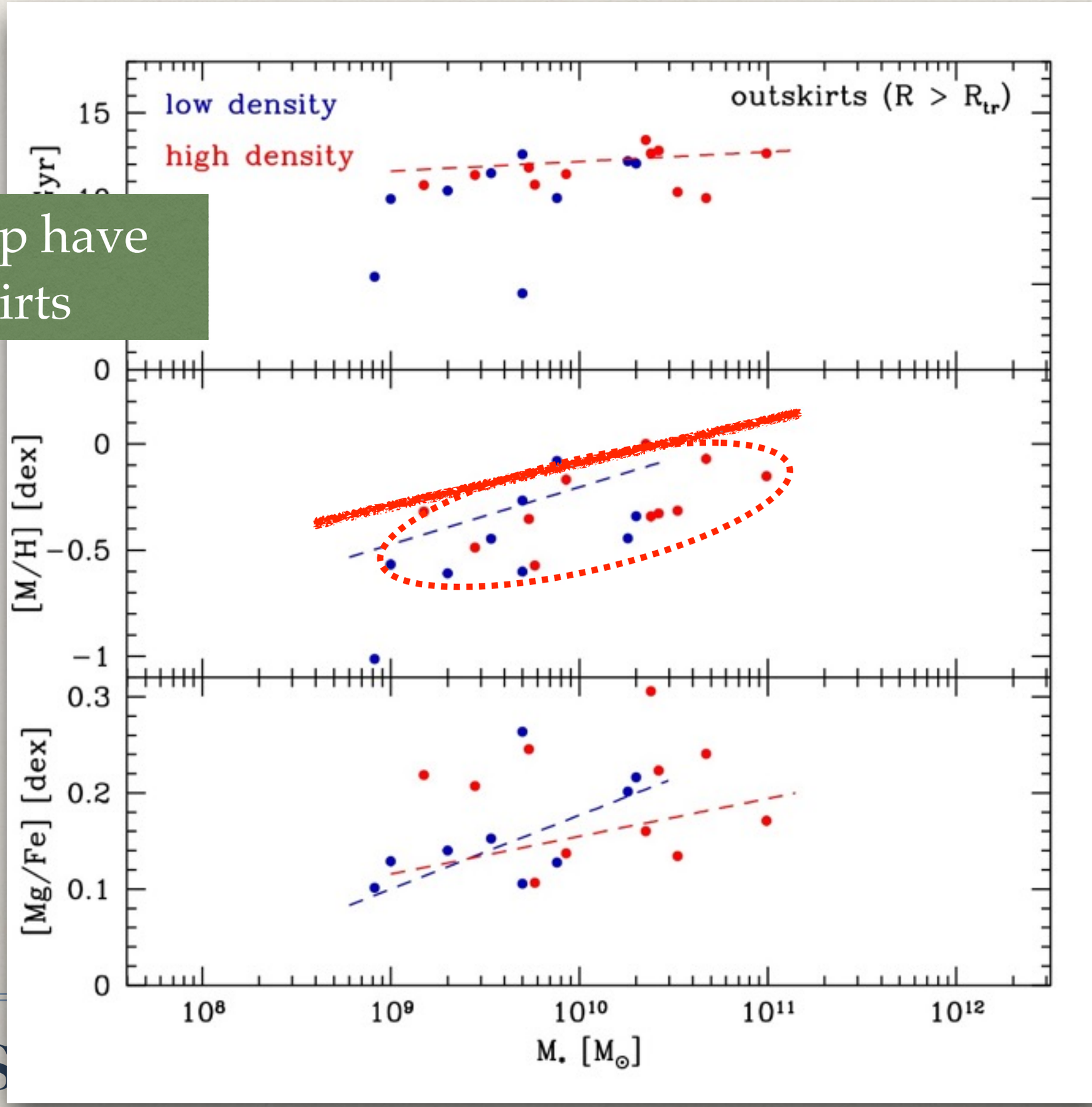
galaxies in the clump are
red and metal-rich
than the infalling galaxies

SP analysis

SP analysis


low density
high density
outskirts (R > R_tr)
Age [Gyr]
15
10
5
0
[M/H] [dex]
0
−0.5
−1
[Mg/Fe] [dex]
0.3
0.2
0.1
0
10⁸
10⁹
10¹⁰
10¹¹
10¹²
M* [M⊙]

galaxies in the clump have metal-poor ouskirts



SP analysis

Conclusive Remarks from FDS + F3D

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Conclusive Remarks from FDS + F3D

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- all are **FRs**, with many of them showing **distinct nuclear components** and **kinematically decoupled cores**
- two out of a total of three show **ionised-gas emission in the centre**
- the **outskirts have lower metallicity** than the bright central regions, which is an indication that the mass assembly of metal-poor satellites continues in the outskirts.

Conclusive Remarks from FDS + F3D

- the **infalling galaxies** are **intermediate** and **recent infallers**, i.e. from the PPS, galaxies that entered onto the cluster potential < 4 Gyr ago

- they are distributed **nearly symmetrically around the core**, in the low-density region of the cluster

- the majority are LTGs with **ongoing star formation**

- they have on average **lower [M/H] and [Mg/Fe]** with respect to galaxies in the clump

- no significant difference in metallicity in the **outskirts** ==> lower accreted mass